JYU DISSERTATIONS 286

Mei Teng Woo

The Influence of Wearable Garments on Postural Regulation and Joint Position Sense Action in Elderly Individuals

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND HEALTH SCIENCES

JYU DISSERTATIONS 286

Mei Teng Woo

The influence of wearable garments on postural regulation and joint position sense action in elderly individuals

Esitetään Jyväskylän yliopiston liikuntatieteellisen tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston päärakennuksen salissa C4
syyskuun 26. päivänä 2020 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Sport and Health Sciences of the University of Jyväskylä,
in University main building, auditorium C4, on September 26, 2020 at 12 o'clock noon.

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
HEALTH SCIENCES

JYVÄSKYLÄ 2020

Editors
Simon Walker
Faculty of Sport and Health Sciences, University of Jyväskylä
Timo Hautala
Open Science Centre, University of Jyväskylä

This is a printout of the original online publication.
Permanent link to this publication: http://urn.fi/URN:ISBN:978-951-39-8294-2

ISBN 978-951-39-8294-2 (PDF)
URN:ISBN:978-951-39-8294-2
ISSN 2489-9003

Jyväskylä University Printing House, Jyväskylä 2020

ABSTRACT

Woo, Mei Teng
The influence of wearable garments on postural regulation and joint position sense action in elderly individuals.
Jyväskylä: University of Jyväskylä, 2019, 106 p.
(JYU Dissertations
ISSN 2489-9003; 286)
ISBN 978-951-39-8294-2
Summary
Diss.

Studies have shown that age-related deterioration of biological systems in elderly populations could contribute to postural instability and falls. This study examined effects of wearing knee length socks (KLS) on postural regulation in community-dwelling older adults. In study I, 49 studies were included for qualitative synthesis and 28 studies for quantitative synthesis. For the cross-sectional study (Study II), 385 older adults aged 65 years old and above, were randomly recruited from the local community. Participants of study III (N = 46) & IV (N = 48) were randomly selected from the participants' pool from study II. A repeated-measures design was used to determine effects of three different intervention treatments – wearing clinical compression socks (mmHg 20–30); wearing non-clinical compression socks (mmHg < 15); wearing commercial socks, and barefoot (Control) on double-limb standing balancing and ankle joint position awareness tasks. The review of published literature showed that somatosensory stimulation through textured insoles (SMD = 0.30) and an application of stochastic resonance (SMD = 0.31) benefit standing balance tasks in older adults. Nevertheless, adverse effects were observed while wearing the wearable garment (SMD = -0.68) in older adults. Result revealed that an increased risk of falling was observed in older adults with subtle cognitive impairment and Berg Balance Scores 40 and below. Wearing compression knee length socks (KLS) significantly reduced the centre of pressure sway parameters ($p < 0.05$) as compared to barefoot condition while performing double-limb standing balance task on a foam surface with vision. Furthermore, both clinical compression and non-compression KLS ($p < 0.05$) were found beneficial on overall joint position sense performance. In conclusion, the study supports the use of knee length socks of various compression levels enhance postural regulation in older adults. Therefore, KLS could be used as an affordable intervention to reform adverse effects of aging on the somatosensory system.

Keywords: Elderly individuals, Knee length socks, Compression, Postural Regulation, Cognitive, Berg Balance Scale, Double-limb standing balance, Joint Position Sense

Author Mei Teng Woo, MSc
Faculty of Sport and Health Sciences
University of Jyväskylä
woo_mei_teng@hotmail.sg

Supervisors Dr. Timo Jaakkola, PhD
Faculty of Sport and Health Sciences
University of Jyväskylä

Prof. Jarmo Liukkonen, PhD
Faculty of Sport and Health Sciences
University of Jyväskylä

Prof. Keith Davids, PhD
Centre for Sports Engineering Research
Sheffield Hallam University

Reviewers Dr. Jeff Breckon, PhD
Department of Sport & Physical Activity
Sheffield Hallam University.

Dr. James Rudd, PhD
Faculty of Science
Liverpool John Moores University

Opponent Prof. Steve Haake, PhD
Academy of Sport and Physical Activity
Sheffield Hallam University

ACKNOWLEDGEMENTS

This dissertation project was part of the FiDiPro project with the aim to understand the potential effect of clothing on enhancing the somatosensory system for the elderly population. The global issue on aging and the fall consequences face by the seniors are the primary motivation for me to choose this group of people. As a volunteer in a senior activity centre in Singapore, I always hear about seniors being susceptible to falling due to the degeneration of the body systems. In the past few years, my mother was facing a similar problem - frequent falls. The falls issue among the seniors has stimulated my interest in the areas of how wearable, mainly compression garments, could be used to enhance balance ability and a postural regulation system.

A reflection of my journey - the roadmap of a PhD journey always presents us with obstacles, challenges, and unexpected situations from time to time. Nevertheless, the beauty of this journey is that you would always find the solutions and be amazed by the outcomes. The satisfaction gained from different phases makes you a better person with more confidence. I was grateful to be given this opportunity to grow and learn more about the topic and to realize my potential and capability. In this process, I have learned many life skills such as problem-solving, critical thinking, research skills, data analytic, communication and writing skills, and networking skills. These are the life skills that closely related to my daily living. Besides, the PhD journey is excellent training for character development whereby you learn: i) how to be patient to manage your research and work commitment, ii) about perseverance for not giving up until you find a unique you, and iii) how to get back from your setback by not giving up.

I want to show my gratitude to the people who have provided me ample opportunities to excel in this journey. First, I would like to express my warmest gratitude to my team of supervisors – Professor Keith Davids, Professor Jarmo Liukkonen, Dr. Timo Jaakkola, and Dr. Chow Jia Yi. They offered me the opportunity to embark on this part-time PhD journey. I want to thank Dr. Chow as the first person who has encouraged me to take up the PhD programme and applied for a research grant from Nanyang Technological University to support my study. Dr. Chow's contribution to my PhD journey is remarkable. I'm honoured to have Dr. Chow in the team to help me in achieving this success in my life journey. I thank Prof. Keith Davids for guiding me to form my first research topic and introducing the PhD opportunity through FiDiPro project in Finland. I am thankful to have Prof. Jarmo Liukkonen and Dr. Timo Jaakkola who have accepted me as their PhD student, provided their constant support on my PhD research and study plans, and their warm hospitality when I visited Finland. I want to thank ZeroPoint (Finland) for the sponsorship of the clinical compression socks in this study. In these 5 years, I am profoundly thankful to have them involved actively in my research by giving constructive feedback on the data collection process, data analysis, and manuscripts writing.

Second, I would like to thank my career coaches – Dr. Michael Koh and Ms. Goy Soon Lan. I thank Dr. Michael Koh for offering the research opportunity with

Dr. Chow in 2010. The project collaboration with Dr. Chow in the early years was a great platform to learn about research. I am also thankful to my department director, Ms. Goy Soon Lan, for her support on my part-time PhD study while working as a lecturer in the school. With her generous support, I was able to apply long leaves to complete some of my modules and focus on my writing in Finland.

Third, I am grateful to have a group of friends for their support during this journey. I wish to take this opportunity to thank all my close friends such as Dr. Ler Hui Yin, Dr. Yeong Poh Kiaw, Ms. Genevieve Phua, Ms. Adelena Loh, and Ms. Lois Ser, for their encouragement and companionship in these 5 years. I want to thank Dr. Marja Kokkonen for spending time to discuss my analysis idea and warm hospitality during my stay in Finland.

Last, I want to express my deepest gratitude to my parents, Mr. Wong Ah Lek and Mdm Soo Chiew Lan, brother Kok Ping, sister-in-law Tze Miang, and sister Mei San, for being there and supporting me on every decision I make. Thank you for your understanding whenever I missed some key family events in these 5 years.

Jyväskylä 02.03.2020
Mei Teng Woo

FIGURES

TABLES

LIST OF ORIGINAL PUBLICATIONS

The dissertation is based on the following original publications, which are referred to in the text by their Roman numerals.

I. Woo, M. T., Davids, K., Liukkonen, J., Orth, D., Chow, J. Y., & Jaakkola, T. 2017. Effects of different lower-limb sensory stimulation strategies on postural regulation – A systematic review and meta-analysis. *PLoS ONE* 12(3): e0174522. https://doi.org/10.1371/journal.pone.0174522

II. Woo, M. T., Davids, K., Liukkonen, J., Chow, J. Y., & Jaakkola, T. 2017. Falls, cognitive function, and balance profiles of Singapore community-dwelling elderly Individuals: Key risk factors. *Geriatric Orthopaedic Surgery & Rehabilitation*, 8(4), 256-262. https://doi.org/10.1177/2151458517745989

III. Woo, M. T., Davids, K., Liukkonen, J., Chow, J. Y., & Jaakkola, T. 2018. Immediate effects of wearing knee length socks differing in compression level on postural regulation in community-dwelling, healthy, elderly men and women. *Gait & Posture*, 66, 63 – 69. https://doi.org/10.1016/j.gaitpost.2018.08.011

IV. Woo, M. T., Davids, K., Chow, J. Y., & Jaakkola, T. Effects of wearing knee length socks on perceptual regulation of action in community-dwelling older adults. Submitted for publication

As the first author of all four publications, my main responsibilities were to i) draft the research questions and the study designs, ii) collect data, iii) perform statistical analysis, iv) write all manuscripts, and v) address reviewers' comments. Throughout the process, the first author wrote all the papers, sought inputs and suggestions from co-authors. The first author also took the responsibility to write a research grant to seek for funding from National Institute of Education, Nanyang Technological University. Studies II, III and IV were supported by the National Institute of education (NIE) Academic Research Fund [grant numbers (ACRF) x RI 8/13 CJY].

ABBREVIATIONS

AP	Anterior-posterior
BBS	Berg Balance Scale
CC	Clinical Compression
CNS	Central Nervous System
CoP	Centre of Pressure
DLS	Double-limb standing
FAI	Functional Ankle Instability
FO	A foam surface with vision
FC	A foam surface without vision
JPS	Joint Position Sense
KLS	Knee Length Socks
ML	Medial-lateral
MMSE	Mini-Mental State Examination
NC	Non-Compression
NCC	Non-clinical Compression
SC	A stable surface without vision
SD	Standard Deviation
SLS	Single-leg standing
SMD	Standard Mean Differences
SO	A stable surface with vision
SRSS	Stochastic Resonance Sensory Stimulation Strategy
TL	Trace length
TMSS	Textured Materials Sensory Stimulation Strategy
WGSS	Wearable Garment Sensory Stimulation Strategy

CONTENTS

1 INTRODUCTION

Bergen and colleagues (2016) mentioned that falls are the leading cause of fatal and nonfatal injuries for older individuals aged ≥ 65 years (Bergen et al., 2016). In 2014, it was reported that 28.7% of older populations in the United States reported falling at least once in the past 1 year. In Singapore, a similar finding was reported where 27.8% of older populations experienced at least one fall a year (Woo et al., 2017a). The data from Singapore National Trauma showed that more than 88% of patients aged ≥ 65 years experienced falls between 2011 to 2013 (Wong et al., 2015). The most frequent initiators of falls in the older people were trips, stumbles and slips; these are the common misjudgement movements of foot-ground interactions resulted from poor proprioception sense (Waked et al., 1997). Waddington & Adams (2003) stated that the soles of the feet and the ankle joints provide essential information about the disposition and movement of the body (Waddington & Adams, 2003).

Age-related deterioration of nervous systems could contribute to postural instability and falls. These deteriorations in older adults include declines in sensory system capacity, neurological functioning, executive function, attention, and processing speed (Glorioso & Sibille, 2011; Thorbahn & Newton, 1996). To date, patients with severe cognitive impairment such as Dementia are related to high falls risk (Mirelman et al., 2012). It is possible that a subtle decline in cognition can contribute to postural instability (Muir et al., 2012) and increases the risk of falling (Gleason et al., 2009). Likewise, lack of ability in balance control is associated with a higher risk of falling (Berg et al., 1992a; Lajoie & Gallagher, 2004; Rose, 2010). Therefore, cognitive functioning and balance abilities are important criteria for participants' selection for testing the effectiveness of lower-limb sensory stimulation strategies on postural regulation and perception regulation of action.

Lower-limb sensory stimulation strategies have become one of the key interventions in somatosensory research to counter ageing effects on postural regulation and proprioception functions. This phenomenon emanates from the argument that footwear such as textured insoles increase sensitivity of plantar cutaneous afferent information thereby increases somatosensory feedback (Corbin et al., 2007; Menant et al., 2008). It is argued that sensorimotor system noise could be enhanced by introducing additional intermittent, intermediate levels of noise via compressive and textured materials (Hasan et al., 2016; Orth et al., 2013). Thereby, it increases postural regulation of an individual by reducing postural sway (Hijmans et al., 2009; Hlavackova & Vuillerme, 2012; Horgan et al., 2009; Losa Iglesias et al., 2012; Menant et al., 2008). Similarly, compression socks and shorts could improve proprioception and standing balance performances, especially in people with lower-limb injuries (Genthon et al., 2010; Kraemer et al., 1998).

The novelty of this study were to compare the effects of various lower-limb sensory stimulation strategies systematically, and to investigate the effects of wearing knee length socks (KLS) with various compression levels, in double-limb standing (DLS) balance and joint position awareness tasks in community-dwelling older adults. The KLS of various compression levels may benefit older adults' perception of somatosensory feedback by picking up relevant information from the background signals. Furthermore, most of the previously published articles did not specify the levels of cognitive and balance abilities of their elderly participants before the implementation of lower-limb stimulation strategies as interventions. Therefore, the current programme sought to examine the effects of knee length socks of various compression levels on postural regulation and joint awareness sense. And, we also aimed to include elderly participants with no cognitive impairment and at low fall risk to go through the KLS intervention.

The purposes of this programme were to i) determine the epidemiology of falling and associated basic background information such as medical conditions, balance ability and cognitive functions of Singapore elderly population and ii) investigate the effects of wearing knee length socks of various compression levels on somatosensory function during a double-limb standing, balancing task and ankle joint position awareness task.

2 REVIEW OF THE LITERATURE

2.1 Falls and risk factors

The definition of "a fall" refers to an unintentional change in position coming to the ground or the lower level (Stoukides et al., 2006; Truter, 2011). Falls are a major threat in elderly people (Al Saif et al., 2012; Wayland et al., 2010). The most frequent initiators of falls in the elderly people were trips, stumbles and slips; these are the common misjudgment movements of foot-ground interactions (Waked et al., 1997). The negative influence of falls to elderly people could be loss of independence, fear of falls, increase mortality (Al Saif et al., 2012; Gale et al., 2016), reduced functioning which increases serious morbidity (Truter, 2011). The decrements in the efficiency of functional mobility lead elderly people to lower levels of self-esteem as they find themselves to be dependent on their daily activities (Moscufo et al., 2009). The above poses potential social issues such as the decrement in social interaction with others which in turn leads to potential mental health issues (Moscufo et al., 2009).

Studies reported that one-third of community-residing elderly people fall each year (Moghadam et al., 2011; Shumway-Cook et al., 1997; Tinetti et al., 1994). The percentage of elderly people reported falling at least once in the past 12 months in the United State (28.7%), United Kingdom (28.4%), Sweden (16.5%), Hong Kong (19.3%), Korea (33.1%) and Singapore (17.2%) (Bergen et al., 2016; Björk et al., 2019; Chan et al., 1997; Chu et al., 2005; Gale et al., 2016; Lee et al., 2018). A recent study in Singapore reported that more than 88% of older patients experienced falls between 2011 to 2013 (Wong et al., 2015).

Fall risk factors are classified as intrinsic or extrinsic factors. Extrinsic factors refer to the environment such as home hazards, and improper footwear (Fabre et al., 2010; Guccione et al., 2012; Lajoie & Gallagher, 2004). Intrinsic factors are related to the physiological changes associated with aging, physical and psychological diseases, medication side effects, and acute illness (Fabre et al., 2010;

Lajoie & Gallagher, 2004). Several intrinsic factors have been identified as fall predictors in elderly people. For example, balance impairment (Berg et al., 1992a; Jeon & Kim, 2017; Muir et al., 2010; Shumway-Cook et al., 1997), cognitive factors such as orientation, working memory and speed of information processing (Fischer et al., 2014; Gleason et al., 2009; Mirelman et al., 2012; Saverino et al., 2016), neurological disorders (Bassiony, 2004; Tangen et al., 2014), and muscle weakness (Moreland et al., 2004).

The major risk factor for falls in older people is balance impairment (Berg et al., 1992a; Muir et al., 2010; Whitney et al., 2012). It was reported that a decline in the ability of balance control is correlated with higher risk of falling (Berg et al., 1992a; Lajoie & Gallagher, 2004; Rose, 2010). Muir et al. (2012) suggested that cognition might play a key role in balance regulation in older adults. It is because the motor and sensory systems are integrated through higher order neurological processes (Muir et al., 2012). The association was found by Tangen and colleagues (2014) where people with severity of cognitive impairment demonstrate a decline in balance ability. Hence, a subtle change in cognition can contribute to postural instability (Muir et al., 2012) and increase the risk of falling (Gleason et al., 2009). The association between cognition and fall risk arise from the perspective of ageing of the frontal cortex and the changes of the white matter of the brain (Gunning-Dixon & Raz, 2000; Pedroso et al., 2011; Raz et al., 2005). The subtle decline in cognition potentially lead to poor decision making, decrement in executive function, attention, and processing speed (Fischer et al., 2014; Gunning-Dixon & Raz, 2000; Raz et al., 2005), and decrements in verbal reasoning and ability (Anstey et al., 2009) which could increase the risk of falling.

2.2 Balance control and postural regulation system

Balance is a generic term to describe the dynamics of body posture to prevent falls (Winter, 1995). Posture refers to the orientation of body segments relative to the gravitational vector (Winter, 1995). It is the ability to regulate the centre of mass concerning its base of support in static and dynamic movements (Horak, 2006). The postural regulation system involves complex integration of information from various multiple sensorimotor processes (Horak, 2006; Shaffer & Harrison, 2007). The primarily responsibility is for keeping the projection of the centre of mass within the limits of the supporting area (Massion, 1994). Lacour et al. (2008) mentioned that the postural regulation system helps individuals to orientate the body's position in space (Lacour et al., 2008).

Reactive, predictive, and anticipatory controls are the three main strategies used in a postural regulation system (Horak, 2006). Reactive control is highly dependent on sensory systems feedback. It involves the interaction among orientation inputs from somatosensory (e.g., proprioceptive, cutaneous, and joint), visual, and vestibular systems (Frank & Patla, 2003; Shumway-Cook & Horak, 1986). The information from various sensory systems is an important aspect for maintaining postural stability during upright stance (Riley & Clark, 2003). For the predictive control strategy, it refers to the ability to control the body movements (e.g., trunk), primarily to prevent the trunk from toppling backward and forward during the alternating push-off and braking motions in walking. These predictable disturbances to balance are associated with anticipatory postural adjustment (Frank & Patla, 2003; Shumway-Cook & Horak, 1986). Anticipatory control relies much more on vision whereby the body would adjust the posture based on the environment. For example, body postures and gait adjustment to avoid obstacles along a walking path.

The body is never perfectly still and continually exhibits irregular, low-amplitude motion, continuous displacements around the actual vertical upright stance. This is termed postural sway. The sway produces a flow of information across the sensory systems and requires an integration of sensory information from multiple sources to maintain postural stability (Oie et al., 2002; Patel et al., 2008). It was reported that the adjustment to the initial body centre of mass over the base of support could be initiated in as little as 100 milliseconds (Frank & Patla, 2003). Ankle strategy is one of the response strategies to postural perturbations (Guccione et al., 2012). This strategy is responsible for activating the muscles around the ankle joint when standing on a stable surface. It was suggested that a significant amount of ankle strength and mobility is required for a successful execution of an ankle strategy. The second main strategy, hip strategy, is the activation of muscles around the hip joint during a sudden and forceful disturbance of base of support while standing in a narrow support surface. Both response strategies are activated to keep the centre of gravity within the base of support during upright stance. Horak (1987) and Winter (1995) mentioned that ankle strategy applies mainly in regulating the posture in the anterior-posterior (AP) direction while hip strategy is the dominant defence in the medial-lateral (ML) direction during quiet standing. Nevertheless, other response strategies such as step and reaching strategies will occur if the large perturbation put individuals at the edge of a fall (Guccione et al., 2012).

2.3 Sensory systems and organisation

Of the three sensory systems responsible for postural regulation, the somatosensory system has the greatest influence in the detection of body sway (Fitzpatrick & McCloskey, 1994) and provides about 70% of sensory information to healthy individuals to regulate the CoP (Horak, 2006; Peterka, 2002). Simoneau et al. (1995) suggested that afferent input from the distal components (lower limbs) of the somatosensory system is as important as the visual system in the control of body posture during quiet stance (Simoneau et al., 1995). Within the somatosensory system, the tactile and proprioceptive sub-systems are responsible in postural regulation. These two sub-systems are responsible for transmitting information to the CNS about the spatial positioning of the body and its limb, via skin mechanoreceptors (Meissner's corpuscles, Pacinian corpuscles, Merkel's disks and Ruffini organ) and proprioceptors (muscle spindles, Golgi tendon organs and joint afferents) (Alan, 2011; Hijmans et al., 2007). Thereby, mechanoreceptors and proprioceptors play a role in regulating posture by responding to fine touch, compression, contortion, vibration, pressure, and position changes in joint angles (Hijmans et al., 2007).

Tactile stimulation to the lower limbs, detected by various joints, muscles and tendons receptors, provides crucial information to the CNS about body segment position and pressure distribution at the feet to achieve postural equilibrium (Guccione et al., 2012; Hijmans et al., 2007; Kavounoudias et al., 1998; Massion, 1994; Menant et al., 2008). Proprioception is the sense of position and movement of the limbs and body which plays a crucial role in regulation of locomotion and body segments position (Gandevia et al., 1992; Gilman, 2002; You, 2005). Proske and Gandevia (2012) stated that muscle spindles are the major sensors for limbs position sense compared to skin receptors and joint afferents (Proske & Gandevia, 2012). The role of muscle spindles is to provide information about the length of the muscles in helping us to judge the limb positions. An optimal proprioception is required and important to interact with the environment effectively (Suetterlin & Sayer, 2014). For example, a good proprioception of precise ankle placement during walking is crucial to avoid tripping and safe ground clearance (Ko et al., 2015).

Meyer and colleagues (2004) mentioned that sensory information from the shanks, ankles, and feet is important for the maintenance of upright balance (Meyer et al., 2004). Studies have shown that feedback from the cutaneous afferents is an important mechanism in the regulating the CoP, especially the pressure changes under the feet (Hijmans et al., 2007; Kavounoudias et al., 1998; Maurer et al., 2001; McKeon et al., 2010; Meyer et al., 2004). Furthermore, the roles of plantar skin receptors are primarily involved in exteroceptive tasks such as evaluate the information about the properties of texture materials and support surfaces in contact to the feet (Maurer et al., 2001). Kavounoudias et al. (1998) described that the foot soles are a "dynamometric map" where ample sensors of the foot soles able to spatially code every pressure exerted against it. This infers that plantar cutaneous afferents could potentially provide valuable feedback to regulate posture during upright stance. Furthermore, other receptors such as Golgi tendon organ at the major knee muscle insertion sites (Ghai et al., 2016), afferent system at the Peroneus Longus muscle (Nishikawa & Grabiner, 1999), cutaneous mechanoreceptors at the dorsum of the feet (Lowrey et al., 2010), and at the anterior and posterior parts of the ankle (Aimonetti et al., 2007; Menz et al., 2006; Simoneau et al., 1995) were found important in providing kinaesthetic cues to somatosensory system.

Nashner et al. (1982) suggested that the CNS generally relies mainly on one sense, either the visual inputs or the proprioception inputs, at a time for regulating posture in a static state (e.g., upright stance) (Nashner et al., 1982). When the upright stance is compromised or any perturbation that alters postural positions, the CNS triggers compensatory postural strategies and sensory re-weighting to regulate posture (Oie et al., 2002). They suggested that the sensory weights are dynamic variables that are dependent upon stimulus motion amplitude. Furthermore, studies have shown that changes in the availability of sensory conditions would result in sensory inputs re-weighting (Nashner et al., 1982; Oie et al., 2002). For example, as sensory condition change, such as an absence of visual feedback, plantar mechanoreceptors can compensate for the missing visual information (Preszner-Domjan et al., 2012). When the somatosensory input is compromised, such as standing on an unstable surface (e.g., foam), the sensory weighting places mainly on vision and vestibular sensory systems for postural regulation (Horak, 2006).

2.4 Age-related changes

Under the normal life cycle, the challenge faced by elderly population is the deterioration of biological systems as they age (Rose, 2010). For example, ageing can result significant decline in sensory systems, decrease spinal-stretch reflex system function, slowing of cognitive ability and increased reaction time (Glorioso & Sibille, 2011; Miyoshi et al., 2003; Seigle et al., 2009). Such deterioration in biological systems causes the delay in triggering the stabilization control systems; affecting postural stability, and unable to restore upright control following a loss in balance (Moscufo et al., 2009). Therefore, older adults would have greater risk of falls as they aged (Rose, 2010).

As people age, neural activity would become less efficient due to the changes in cutaneous sensitivity and receptor morphology. This could increase the sensory and vibration threshold needed for accurate perception (Perry et al., 2008; Rose, 2010; Woo et al., 2014). Evidence suggests that degeneration of somatosensory function, namely, insensitivity of peripheral sensory receptors from the soles, is the main contributor to postural instability (Qiu et al., 2012). The proprioception acuity degradation was primarily due to the decline of peripheral mechanoreceptors in the muscles, skin, and joints (Goble et al., 2009; Shaffer & Harrison, 2007). Robbin et al. (1995) found that sensitivity of foot position declines with age, mainly because of the receptors degeneration of the plantar tactile receptors. In addition to the peripheral sensory loss, central sensory selection, and re-weighting processes are thought to degrade with increasing age (Horak et al., 1989).

Generally, proprioception and the stability of posture decline with age (Błaszczyk & Michalski, 2006; Goble et al., 2009). It was found that older adults had higher errors for the matching of targets located farther from the original position (Goble et al., 2009). Madhavan and Shields (2005) found that the decline in dynamic position sense was associated with decreased balance and an impaired perception of physical function (Madhavan & Shields, 2005). Many studies showed a significant increase of centre of pressure (COP) velocity, path length, and sway area with age (Du Pasquier et al., 2003; Prieto et al., 1996; Seigle et al., 2009). Limited studies reported gender differences were found in age-related deterioration of postural sway (Bryant et al., 2005; Kim et al., 2012; Masui et al., 2005; Riva et al., 2013). Research has reported that older adults with poor proprioceptive acuity showed larger sway in the AP direction during an upright stance on a compliant surface, regardless of vision conditions (Lord et al., 1991). Tucker and colleagues (2010) found that older adults response slower during the initiation of AP and ML sway while performing the double-limb standing balance task. The velocity and displacement of the CoP in the AP direction were found correlated with age that potentially could be the indicator for fall (Du Pasquier et al., 2003). In addition, a review study done by Piirtora and Era (2006) suggested that ML CoP related parameters such as mean speed and amplitude can provide valuable information in predicting future falls in elderly population. From the literature review, it showed that the CoP parameters changes during upright stance and position sense in a matching task were primarily used by researchers to study the effect of aging of somatosensory system.

2.5 Mechanism of applying lower-limb sensory stimulation strategies

The underlying mechanism behind the enhancement of proprioception information from applying lower-limb stimulation strategies could be explained by using ecological dynamics framework. The functional role of variability induced in the sensorimotor system by textured insoles acts as a form of "essential noise" (Davids et al., 2003). The essential noise is deemed to help individuals to regulate actions in a complex environment (Davids et al., 2003). It is argued that sensorimotor system noise could be enhanced by introducing additional intermittent, intermediate levels of noise (Hasan et al., 2016; Orth et al., 2013). It is believed that additional stimulations through lower-limb stimulation strategies (e.g., compression garments; textured materials) would help individuals to pick up information from the background signals and thereby enhance the perception of somatosensory feedback (Davids et al., 2003).

The spinal-stretch reflex system is one of the main systems to regulate posture during quiet stance standing as well as in perturbed situations (Taube et al., 2008). The additional stimulation through wearable garments, textured insoles and electrical stimulation might facilitate the spinal reflex system, specifically invoking the Hoffmann Reflex (H-reflex), in order to adapt and respond to demanding tasks (Nishikawa & Grabiner, 1999; Taube et al., 2008). For example, study showed that wearing an ankle brace increases afferent transmission at the Peroneus Longus muscle (Nishikawa & Grabiner, 1999). This enhances the motor neuron excitation and providing additional active impact for proprioceptive control of movement in the dorsiflexor muscles (Larsen et al., 2015).

2.6 Effects of lower-limb sensory stimulation strategies

2.6.1 Wearable garments

Wearable garments such as tapes, braces, and compression garments were mainly used in the areas of prevention of injury and re-injury (Baier & Hopf, 1998; Kuster et al., 1999; Robbins et al., 1995; Simoneau et al., 1997). The main focus of the previous research was centred on how disrupted proprioception could be enhanced by using wearable garments. Baier and Hopf (1998) found that wearing a flexible ankle orthosis significantly reduced ML sway velocity in people with functional ankle instability. It was suggested that the adhesiveness of the tape acts on the skin augmented the information transmission at cutaneous receptors which enhances the anticipation of the foot position (Robbins et al., 1995). Likewise, studies also investigated the effects of wearing compression shorts and sleeves on joint position sense and postural regulation during a single-leg landing task (Kraemer et al., 1998; Kuster et al., 1999). The findings of Kuster et al.'s (1999) study revealed that the compressive sleeve intervention reduced postural sway in the anterior-posterior direction.

Recent investigations showed that the beneficial effect of using wearable garments were observed on somatosensory system in young healthy adults (Kunzler et al., 2013; Robbins et al., 1995; Vuillerme & Pinsault, 2007), athletes (Michael et al., 2014; Sperlich et al., 2013), elderly individuals (Hijmans et al., 2009), and people with lower-limb injury (Genthon et al., 2010; Palm et al., 2012; You et al., 2004). For examples, Kunzler et al. (2013) and Vuillerme and Pinsault (2007) indicated that the medical and athletic adhesive tapes on the ankle decrease CoP velocity and CoP sway area during a double-limb standing balance task and compression stocking was found to reduce the CoP trajectories amplitude. Michael et al. (2014) found that compression shorts increased the total timing in unipedal standing balance task in a more challenging condition involving visual occlusion in a group of female athletes. Sperlich et al. (2013) suggested that using lower leg clinical compression (20–40 mmHg) may improve alpine skier's tuck position. Woo et al. (2014) suggested that simple tactile stimulation and localised knee-high compression socks and non-compression socks had the similar functions regularization of anterior-posterior (AP) and medial-lateral (ML) motions, as seen under barefoot conditions in postural regulation among physically active elderly individuals with a low risk of falling. Nevertheless, localized compression on the ankle was not beneficial for postural regulation during static balance performance in a group of elderly individuals (Hijmans et al., 2009). Similarly, Papadopoulos et al. (2007) found that ankle braces with 30kPa and 60kPa pressure did not benefit the balance control strategy of the central nervous system (CNS) (Papadopoulos et al., 2007).

Studies have also shown that judgment of ankle position and orientation of plantar foot surface with respect to the leg could be improved by wearing wearable garments (Robbins et al., 1995; Robbins & Waked, 1997; Simoneau et al., 1997). Studies have shown that compression garments (Ghai et al., 2016; Hijmans et al., 2009; You et al., 2004), tapes (Iris et al., 2010; Robbins et al., 1995; Simoneau et al., 1997), braces and sleeves (Herrington et al., 2005; Van Tiggelen et al., 2008; Wu et al., 2001) improved joint position sense at the ankle and knee joints. Barss et al. (2018) suggested that wearing compression sleeves could increase precision and sensitivity at the joint (Barss et al., 2018). Herrington et al. (2005) showed that application of non-compression knee sleeves improved proprioceptive acuity in healthy and physically active subjects. Similarly, recent research found that below-knee compression garments improved knee-joint proprioception, by reducing the mean errors of an active repositioning task, in young adults (Ghai et al., 2016). In contrast, compression garment worn above the knee did not improve joint position sense at the knee in healthy adults (Négyesi et al., 2018). These studies found that mean joint position error was reduced either by wearing a non-compressive or compressive garment for joint position sense tests. To date, there was only a study examining the effects of compression wearable garments in the elderly population. It showed that the application of ankle-foot orthoses (AFOs), ankle support, and compression of the ankle and foot have an association with improvement of ankle joint position sense (Hijmans et al. 2009).

2.6.2 Textured materials

Footwear with textured materials such as textured insoles have become the focus of attention in somatosensory studies. Beneficial results of using textured materials were observed in young healthy adults (Aruin & Kanekar, 2013; Corbin et al., 2007; Menz et al., 2006). It was reported that wearing textured insoles reduced postural sway (Corbin et al., 2007; Palluel et al., 2008), and improve the symmetricity of static and dynamic postural response in young individuals (Aruin & Kaneka, 2013). Menz et al. (2006) found that passive stimulus through textured materials (e.g., Velcro) applied to the skin of the leg significantly reduce body sway during standing.

Studies have also shown a positive relationship between postural regulation and somatosensory feedbacks contributed by textured insoles in elderly individuals (Hijmans et al., 2007; Orth et al., 2013; Qiu et al., 2012). A meta-analysis by Orth and colleagues (2013) stated that external stimulation (e.g., textured materials) on cutaneous receptors could improve perceptual-motor system functionality for elderly individuals. Similarly, a systematic review proposed that vibrating insoles and tubing at the plantar surface of the feet benefitted older people in maintaining their balance and better postural control (Hijmans et al., 2007). For examples, Qiu and colleagues (2012) suggested that textured insole surfaces, both hard and soft, reduced the postural sway during standing in older people. Losa Iglesias and colleagues (2012) also indicating that hard insole surfaces may be more effective compared to soft insole for reducing the fall risk. This study mentioned that more rigid insoles actually promote a more neutral alignment of the talocrural joint in standing position, limit the range of foot pronation, and thereby potentially improve the ankle joint stability (Losa Iglesias et al., 2012). Furthermore, Hatton et al. (2009) found that wearing textured insoles significantly lower gait velocity, step length and stride length in older adults, aged above 65 years old (Hatton et al., 2009). Likewise, the high-collar shoes were found significantly increased tactile sensory feedback around the ankle and assisted in reducing anterior-posterior body sway following gait termination (Menant et al., 2008). Nonetheless, there were studies which found no beneficial effects in the older adults (Qiu et al., 2013; Qu, 2015; Wilson et al., 2008). Wilson et al. (2008) reported no beneficial effect of using grid and dimpled texture insoles in middle-aged women.

The positive results were also found beneficial for people with neuropathy conditions (Jenkins et al., 2009; Kelleher et al., 2010; Qiu et al., 2013). For example, Kelleher and colleagues (2010) suggested that textured insoles alter the gait patterns in people with multiple sclerosis. Qiu et al. (2013) found that textured insoles decreased medial-lateral sway area and medial-lateral sway standard deviation in people with Parkinson's Diseases (PD) during static standing balance task on both stable and foam surfaces, with and without vision. Similarly, facilitatory ribbed insoles were found increased time spent during single-limb support phase of a gait cycle. This implied an improvement in overall gait stability in PD patients (Jenkins et al., 2009).

2.6.3 Stochastic resonance

An application of SR, the use of sub-threshold electrical or mechanical stimulation (white noise) for stimulating soles of the feet, has also received substantial research attention in postural regulation. Research found positive effects of using various intensities of electrical noise on balance control in patients with functional ankle instability (FAI) (Rose & Guskiewicz, 2006; Ross, Scott & Arnold, 2012; Ross et al., 2007; Ross, 2007), older adults (Amiridis et al., 2005; Gravelle et al., 2002), and young adults (Dickstein et al., 2005; Kimura & Kouzaki, 2013; Magalhães & Kohn, 2014). In young adults, the application of low-amplitude transcutaneous electrical nerve stimulation to the posterior aspect of the lower limbs decreased in postural sway variables such as average sway velocity, absolute values of maximal and minimal ML and AP velocities during static balance standing stance (Dickstein et al., 2005). Similarly, an introduction of imperceptible electrical noise deemed to improve the transmission of proprioceptive information in the lower limbs, resulted in a significant decreased in postural oscillations during quiet bipedal stance (Kimura & Kouzaki, 2013; Magalhães & Kohn, 2014).

Ross and Guskiewicz (2006) suggested that SR stimulation improved the FAI group's time-to-stabilisation during single leg jump-landing task in ML direction after 2 weeks of training, and AP direction after 4 weeks of training. They speculated that the application of SR stimulation might have enhanced the detection of weak sensory feedback signals that is important for maintaining postural stability (Rose & Guskiewicz, 2006). In the elderly population, Gravelle et al. (2002) indicated that low-level input noise through electrical or mechanical stimulation could enhance the sensitivity of the human somatosensory system. Their findings showed that application of electrical noise at the knee enhances older adults' balance ability by decreasing the CoP path length, sway area, medial-lateral Standard Deviation (MLSD) and maximum AP excursion. Similarly, Amiridis et al. (2005) found that electric stimulation training resulted in decreased postural sway, higher ankle muscles EMG activity, and greater stability of the ankle joint in a group of elderly people. From the motor system perspective, introduction of weak input signals through the tendon of a parent muscle enhanced the sensitivity of the muscle spindle receptors to modulate performance in complex motor tasks (e.g., for balance) (Cordo et al., 1996). By exploiting the phenomenon of SR, the postural regulation system can be restored for people who lost the resiliency and adaptive capacity due to aging and diseases (Sejdić & Lipsitz 2013). Therefore, white noise stimulation boosted detection of sensorimotor signals through SR, subsequently enhancing the functioning of the postural regulation system.

2.7 Measurement properties and feasibility of assessment tools

Measurement properties such as reliability, validity, responsiveness, and feasibility are important for researcher in the field of sport, medical and health-related fields (Robertson et al., 2014). Top ten items relating to methodological quality are test-retest reliability, intra-rater reliability, inter-rater reliability, content validity, discriminant validity, sensitivity to change, minimum important difference, interpretability, familiarity required and duration (Robertson et al., 2017).

The following were the primary measurement tools used in this study (see 4.6 for detail description). Mini-mental state examination (MMSE) and the Berg Balance Scale were used in the cross-sectional study to identify the cognitive and balance abilities of the elderly people. The double-limb standing (DLS) task was used to measure the static balance of elderly standing on a balance platform. Joint position awareness was then measured via modified slope box.

2.7.1 Mini-mental state examination

Examination of cognitive processes is a popular assessment component for fall risk prediction (Muir et al., 2012). A meta-analysis review done by Muir et al. (2012) reported that Mini-Mental-State Examination (MMSE) was the most common cognitive measurement tool used by researchers globally. The review concluded that a score below 24 in MMSE was correlated to moderate and high risk of serious fall-related injuries. Anstey et al. (2006) suggested that MMSE scores predicted rates of falling in very old adults. Gleason et al. (2009) provided more insightful information between MMSE scores and risk of falling, where the decrement from a score of 30 increased the risk of falling. Thus, MMSE scores could be adopted by local health care sectors to identify the risk of falling among healthy elderly individuals. O'Connor et al. (1989) found high test-retest reliability at 0.84 of using the MMSE on a group of older adults, aged 75 years old and above. The finding was in-line with the study done by Folstein et al. (1975) where high test-retest reliability was found at 0.89. Furthermore, it was reported that inter-rater reliability was at 0.8 (Folstein et al., 1975). In terms of the validity of MMSE, O'Connor et al. (1989) reported high sensitivity of 86% and specificity of 92% at a cut-off point of 24 that reflects well on the MMSE as a screening test for cognitive assessment. A comprehensive review done by Tombaugh et al. (1992) further concluded that MMSE test had moderate-to-high levels of sensitivity (69–100%) and specificity (62–100%) of using MMSE in older adults.

2.7.2 Berg Balance Scale

Balance related tests are one of the famous fall-risk assessment tools for fall prediction (Scott et al., 2007). Berg Balance scale (BBS) is the most commonly used subjective assessment tool globally in predicting falls among older people (Berg et al., 1992b). They found that BBS test can predict the occurrence of multiple falls, and it was strongly correlated with functional and motor performance, particularly in stroke patients. In 1997, Shumway-Cook and colleagues (1997) suggested the BBS test as a highly predictive test for examining falling in elderly. It was recommended that a score between 45 and 53 for the Berg Balance Test correspond to individuals with a 20% to 75% probability of falling. The total BBS scores contributed significantly to the prediction of falls with 89% sensitivity and 96% specificity (Lajoie & Gallagher, 2004). In 2006, Wang and colleagues conducted an investigation on the psychometric properties of the Berg Balance Scale in a community-dwelling elderly resident population in Taiwan. They found that BBS had good internal consistency reliability and a good inter-rater reliability. This finding supported the outcome studies by Berg et al. (1992) where they reported the test-retest and intra-rater reliability for older adults with ICCs of 0.91 and 0.97, respectively. Furthermore, Jácome et al. (2016) found that the validity of the BBS was high and it was strongly correlated with other balance tests. They further supported that BBS was a valid test to identify fall status. Similarly, Marques et al. (2016) reported that BBS is a valid test to predict falls in older adults (Marques et al., 2016).

2.7.3 Double-limb Standing Balance Task

Static balance tests (i.e., quiet stance tasks) are often used as part of functional assessment in elderly populations (Bradley, 2011). To increase the difficulty of the task, unstable surface such as foam and with the occlusion of vision, are typical design used in postural regulation research (Lord et al., 1991; Qiu et al., 2012; Qiu et al., 2013; Tomomitsu et al., 2013; Woo et al., 2014). Lord et al. (1991) reported that greater reliance is placed on somatosensory information when vision is excluded. For the duration of the static balance task, it was suggested that optimum reliability obtained was at 20–30 s trial durations (Le Clair & Riach 1996). Furthermore, a 30-s trial length was suggested as it produced acceptable reliability even during eyes closed condition (Doyle et al., 2006). To date, no study has been carried to investigate the reliability and validity of double-limb standing balance test in elderly population. There was only 1 study investigate the reliability of DLS in young adults where they reported ICCs of 0.67 and 0.73 for balance test under the eyes closed and eyes open conditions, respectively (Fredrik et al., 2015).

2.7.4 Joint Position Awareness

Joint position sense (JPS) test is an assessment of proprioception (Suetterlin & Sayer, 2014). JPS determines the participant's ability to comprehend a presented joint angle (Ribeiro & Oliveira, 2007). One of the assessments is via surface slope test where participants are asked to indicate the steepness of a slope box (Hijmans et al., 2007; Robbins & Waked, 1997) Slope box is a practical way to measure joint position awareness (Hijmans et al., 2009; Robbins et al., 1995). Similar to the other studies' measures (Hijmans et al., 2009; Robbins et al., 1995), the participant stood and placed their body weight on the on the modified slope box to estimate the steepness. Halasi and colleagues (2005) stated that the overall reliability of using the slope box to test the joint position sense was high at 0.92. Similarly, Robbins et al. (1995) found high test-retest reliability (0.91) of using the slope box method (Robbins et al., 1995). To date, no study has investigated the validity of using slope box to test the joint position sense at the ankle joint.

2.8 Rationale of the study

Among the peripheral and central components of the visual, somatosensory, and vestibular systems, tactile-proprioceptive feedback from the somatosensory system is more susceptible to ageing, which increases the risk of falls (Qiu et al., 2012). The motivation behind this proposed research is rooted in ideas of deterioration of sensory system performance and the concept of sensory systems reweighting on their contributions to action regulation. The proposed research programme builds on recent published works examining the effect of lower-limb sensory stimulation strategies (e.g., textured footwear; braces and tapes, an application of Stochastic Resonance) on the functions of the somatosensory systems (Corbin et al., 2007; Hijmans et al., 2007; Perry et al., 2008). Researchers have found that lower-limb sensory stimulation strategies increases somatosensory feedback, which increases postural regulation by reducing postural sway (Losa Iglesias et al., 2012; Orth et al., 2013; Qiu et al., 2012), and improve the joint position sense (Hijmans et al., 2009; Robbins et al., 1995; Robbins & Waked 1997). Among all the different types of sensory stimulation strategies studied, wearable garments, especially socks, have received little research attention on its effect on postural regulation, although they are common footwear in daily living.

Socks are the first contact point of cutaneous receptors in the soles; yet, they have not received adequate empirical attention. To date, research in socks is limited; for example, prevention of foot lesions such as blisters, ulcers, calluses and sores (Dai et al., 2006); biomechanical response in walking and running (Tsai &

Lin, 2013); slipping and falling (Hübscher et al., 2011; Koepsell et al., 2004). To date, only scarce scientific evidence can be presented to support the fact that proprioceptive feedback at the lower-limb is improved by the use of wearable garments in the elderly population. It is argued that sensorimotor system noise could be enhanced by introducing additional intermittent, intermediate levels of noise via compressive and textured materials (Hasan et al., 2016; Orth et al., 2013; Woo et al., 2017b). This may help performers to pick up information from the background signals to enhance the perception of somatosensory feedback (Davids et al., 2003). Wearable garments such as compression socks are able to stimulate proprioceptors (muscle spindles, cutaneous receptors, joint receptors) through contortion and compression which could enhance the level of sensorimotor system noise, thus providing better neuromuscular control and performance (Davids et al., 2003; Nishikawa & Grabiner, 1999; Sejdic & Lipsitz, 2013).

Therefore, I sought to address the issue on how below-knee proprioception could be improved via a non-invasive intervention (e.g., wearable garments), helping community-dwelling elderly individuals to improve postural regulation and minimize the joint position sense errors and potentially forming a strategy to reduce risk of falling.

3 THE PURPOSE OF THE STUDY

The primary aim of this programme was to investigate the effectiveness of lower-limb sensory stimulation strategies, specifically knee length socks (KLS) of various compression levels, on somatosensory functions in community-dwelling, healthy, elderly people. In the selection process of participants, this study also aimed to collect socio-demographic information, cognitive ability and balance profile of a group of elderly individuals living in Singapore.

Primary aims:

1. Study 1: To review systematically and meta-analyse the effects of lower-limb stimulation strategies on sensory regulation of postural control and balance performance on various populations and under different task constraints.
2. Study 2: To profile and to compare occurrence of falls, and cognition and balance profiles across people in elderly age categories in a sample of Singapore's elderly population.
3. Study 3: To examine acute effects of wearing knee length socks of various compression levels on somatosensory function in community-dwelling healthy elderly men and women during a double-limb standing, balancing task.
4. Study 4: To examine acute effects of wearing knee length socks of various compression levels on ankle joint position sense in community-dwelling healthy elderly men and women.

4 METHODS

4.1 Study design

The present study design is presented in Figure 1.

In study I, systematic review was used to consolidate publications concerning the effects of different lower- limb stimulation strategies on postural regulation and stability. Thereafter, meta-analysis was conducted to derive the pooled estimate of treatment effectiveness.

A cross-sectional study design was used in study II. A total of 385 participants were recruited via random sampling approach (see 4.3 for detail description). The profile of the Singapore elderly people such as socio-demographic characteristics, balance abilities and level of cognitive functions were collected through face-to-face interview.

A repeated-measures design was used to investigate the effects of different treatments (barefooted; wearing clinical compression socks; wearing non-clinical compression socks, non-compression socks) in a counterbalanced order, while performing static balance (Study III) and joint position estimation (Study II) tasks. The participants for study III and IV were randomly selected from the pool of participants of study II.

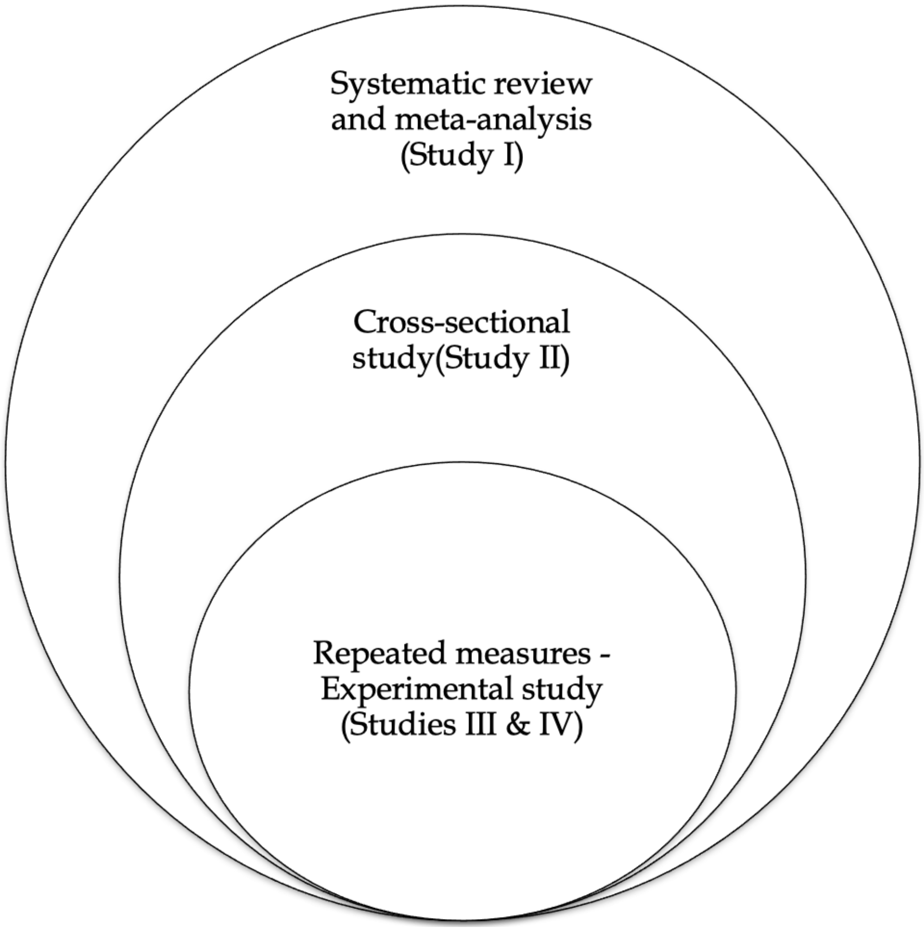


FIGURE 1 The design of the study.

4.2 Systematic review and meta-analyses (Study I)

4.2.1 Selection of studies

Electronic databases such as EBSCO, Science Direct, PubMed, Taylor and Francis, Google Scholar, and Scopus were searched to identify all publications associated with the effects of different lower- limb stimulation strategies on postural regulation and stability. In addition, a hand-conducted search of reference lists was manually checked to identify studies not captured in the electronic database searches. In the context of this study, the lower-limb stimulation strategies were grouped into three main categories based on the characteristics. Compression garments (sleeves; socks), braces, and tapes were grouped as Wearable Garments (WGSS). Textured insoles and footwear were grouped as Textured Materials (TMSS). Last, the implementation of white noise and electrical stimulation were grouped as an application of Stochastic Resonance (SRSS).

Two groups of standardized search keywords were used in searching relevant articles. The first group of keywords was related to lower-limb stimulation strategies: Textured or Textured insoles or footwear, compression or compression garments and stocking, tapes and braces, application of Stochastic Resonance. The second group of keywords was related to tasks: Postural Control and Balance.

4.2.2 Inclusion and exclusion criteria

All the potentially relevant articles were screened and retrieved from the electronic database based on the abstract and titles during the initial screening phase by the first reviewer. Then, the retrieved articles were evaluated separately by the first and fourth authors using the inclusion and exclusion criteria (Table 1) for the full review, with any disagreement resolved by consensus.

TABLE 1 Inclusion and exclusion criteria – systematic review and meta-analysis

Inclusion criteria	Exclusion criteria
1. No restrictions on study design. 2. Studies published in English between 1995 and October 2016. 3. Studies investigating the effects of behavioural measures of textured materials (insoles; stocking), wearable garments (compression garments; braces; tapes), and application of Stochastic Resonance during tasks involving postural stability and balance (static; dynamic) in non-fatigue conditions. 4. The primary outcome measures consisted of the center of pressure (CoP) related measurements, the center of mass (CoM), distance reach, balance time, and gait variables. 5. The primary outcomes included in the meta-analysis were the center of pressure (CoP) related measurements such as CoP sway and standard deviations (SD) in medial-lateral (ML), and anterior-posterior (AP) directions; path length; recurrence quantification analysis (RQA) measurements. 6. In the meta-analysis, studies were required to report means and standard deviations of outcome measures interacting with lower-limb stimulation strategies.	1. Studies that use cumbersome and expensive equipment in investigating vibration effects on postural ability, which is more complex and costly for end-users, compared to the simpler addition of electrical stimulation, textured, and wearable materials. Furthermore, vibration effects usually produce stimulation above the consciously perceived threshold level, which would negate the role of Stochastic Resonance in enhancing proprioception and haptic perception at a subthreshold level. 2. Studies where outcome variables are not compatible for comparison, (means and standard deviations) in the meta-analysis. 3. Studies in stroke, diseases resulting in neuropathy (e.g. Multiple Sclerosis and Parkinson Disease) and cerebral palsy populations, with some damage to the brain, impairing physical mobility and postural control mechanisms.

4.2.3 Procedure and analysis

All the selected articles for a full review that met the inclusion criteria would go through the methodological quality assessment, using the Cochrane Collaborations tool to evaluate the risk of bias by both reviewers. For systematic review, key information such as sample size, participant characteristics, tasks, equipment used, balance-related measurements, and main outcomes of the study were tabulated in a summary table.

In the meta-analysis, Unbiased (Hedges' *g*) standardized mean differences (SMD) and 95% confidence intervals (CI) were calculated for continuous outcomes (Morris & DeShon 2002). The calculated effect size of the multiple treatments was combined and treated as a single effect size for studies that investigated more than two treatments (Borenstein et al., 2009). For the articles that have multiple stages of task design, the most appropriate stage (pre- or post-treatment) was chosen, based upon its relevance to the objective of this analysis. Thereafter, Review Manager (RevMan computer program, version 5.3.5 Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) were used for the calculation of pooled effect size, p-value, z-score, Tau^2, heterogeneity (I^2). The following settings were used: data type – generic inverse variance; statistical method – inverse variance; analysis model – random effects; effect measure – standardized mean difference (SMD); study and total confidence interval – 95%.

An effect size of 0.1 is considered small, an effect size of 0.3 is medium, and an effect size of 0.5, large (Borenstein et al., 2009). Consequently, pooled effect size, 95% confidence interval, P-value, and heterogeneity (I^2) were calculated per subgroup, per study. An alpha level of 0.05 (two-tailed) was used to test whether the average effect size was significantly different from zero in each subgroup.

4.3 Participants (Study II, III & IV)

There were two main phases of research in this programme. In phase 1 (study II), 385 community-dwelling, elderly individuals age 65 years and above were recruited randomly from Singapore communities. The recruitment process started by sending invitation emails to local senior activity centres (e.g., Sarah, Kreta Ayer, and SilverACE), government organisations (e.g., People's Association and Community Development Council) and social development groups (e.g., Thye Hua Kwan Moral Society, Churches, and Mosques) across Singapore to obtain their approvals for announcing the recruitment of elderly participants of this project in their respective centres. The classifications of the age groups of the elderly people were based on the Singapore's Department of statistics (2007). Therefore, the age groups of the elderly were identified as "young-old (65-74 years)", "medium-old (75-84 years)" and "oldest-old (above 85 years)" in this study (Singapore Department of Statistic, 2007). Specific inclusion criteria for phase 1's participants were ability to walk independently, able to follow instructions, and freedom from diagnosed neurologic diseases (e.g., Parkinson's and Alzheimer's diseases). Exclusion criteria included history of severe rheumatic arthritis, neuropathy injury, recent stroke events (< 18 months), brain injuries, and diagnosed cognitive dysfunctions.

Participants' characteristics of study III and IV is shown in Table 2. From the participants' pool in phase 1, a total of 154 individuals met the inclusion criteria of phase 2 (study III & IV). The inclusion and exclusion criteria were chosen with reference to previous studies (Hatton et al., 2012; Hijmans, et al., 2009; Qiu et al., 2012). Specific inclusion and exclusion criteria of study III and IV were presented in Table 3. Each participant was given a number by using the excel randomize function. Thereafter, researcher contacted the participants, in the ascending order (number), to check their availability and interest to participate in study III (N = 46) and IV (N = 48).

Ethics approval was sought from the ethical committee of the University of Jyväskylä and Nanyang Technological University, Singapore, for this research programme. Informed consents (Appendix 1) were obtained from all participants, and the procedures used in the study were in accordance with both institutions' ethical guidelines.

TABLE 2 Participants' characteristic

	Study II (N = 385)		
	Young-old (n = 212)	Middle-old (n = 146)	Old-old (n =27)
Age (years old)	69.63 ± 2.97	79.14 ± 2.95	88.22 ± 2.91
Height (cm)	156 ± 8	153 ± 8	151 ± 7
Weight (kg)	60.56 ± 11.05	54.10 ± 9.82	51.44 ±9.58

	Study III (N = 46)		Study IV (N = 48)	
	Men (N = 23)	Women (N = 23)	Men (N = 24)	Women N = 24)
Age (years old)	75.2 ± 5.1	72.8 ± 5.8	74.4 ± 4.9	71.9 ± 5.8
Height (cm)	162.3 ± 6	153.7 ± 6	163.1 ± 6	153.5 ± 7
Weight (kg)	57.9 ± 9.5	59.8 ± 11.2	62.1 ± 11.5	58.9 ± 10.1

TABLE 3 Inclusion and exclusion criteria – study III and IV

Inclusion criteria		Exclusion criteria	
Study III	Study IV	Study III	Study IV
1. ability to walk independently without using any assistive devices (e.g., walking stick; umbrella), 2. no history of falling in the past 12 months 3. Mini-Mental State Examination (MMSE) score > 24 (normal). 4. Berg Balance task Score > 40 (normal)	1. ability to walk independently without using any assistive devices (e.g., walking stick; umbrella), 2. no history of frequent falls (More than 2 falls during past 1 year), 3. Mini-Mental State Examination (MMSE) score > 24 (normal).	1. Elderly individuals with any diagnosed muscular and neurological diseases, deformities of ankles or feet, demonstrated lack of understanding on the task's instructions, recent stroke events (< 18 months), and brain injuries.	

4.4 Apparatus (Study II, III & IV)

In study II, Fallproof Health and Activity Questionnaire (Rose, 2010) (Appendix 2) was used to collect the background information such as medical conditions, falls frequency, description of falls and physical activities. Mini-Mental State Examination (MMSE) questionnaire (Appendix 3) was used to categorise the cognitive levels. Berg Balance Scale test (Appendix 4) was used to identify balance ability.

In study III and IV, three types of knee length socks of various compression with similar thickness were used as treatment interventions - clinical level compression (CC) of 20–30 mmHg pressure (Zeropoint, Finland), non-clinical level compression (NCC) of 8–15 mmHg (X-bionic, Switzerland), and non-compression (NC) models commercial (Mizuno, Japan).

A balance platform (Hur, Finland) was used to collect the stabilometric data of double-limb, standing task. A 10-cm thick foam pad (50 x 50 x 10 cm; Density: 30 kg/m$^{3)}$ was used to place on top of the balance platform to create an unstable surface. Joint position sense awareness data was collected by using a modified slope box. It was designed to be altered between 0° and 20° in steps of 2.5° in the direction of plantar flexion. The apparatus used in study III and IV is shown in Figure 2.

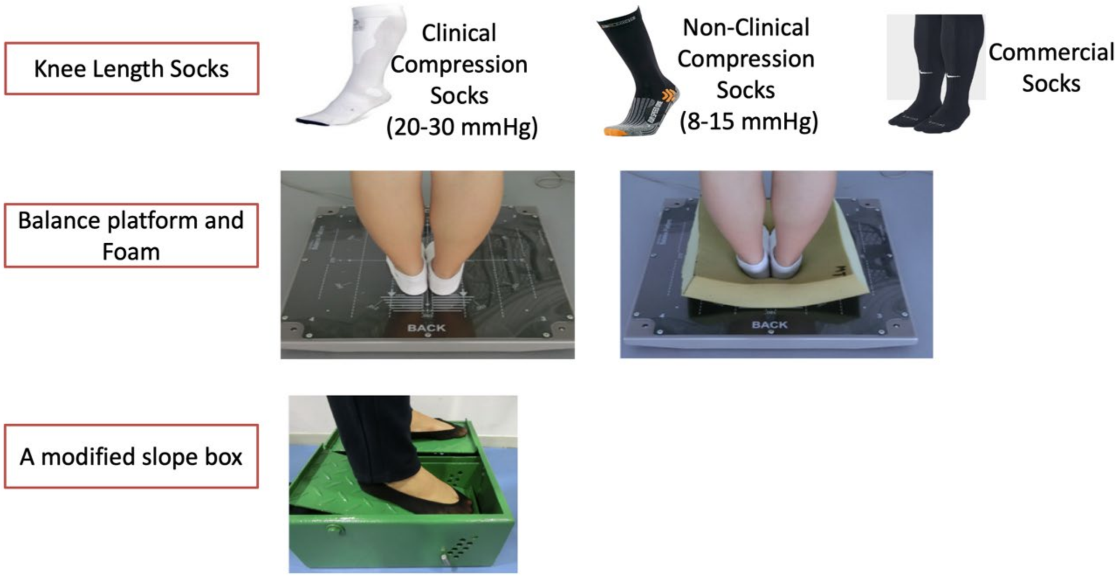


FIGURE 2 Apparatus used in studies III and IV

4.5 Procedure (Study II, III & IV)

In phase 1 (study II), researcher conducted the interviews, cognitive and balance tests in the respective local community centres. Participants were required to answer a set of questionnaire (Fallproof Health and Activity), via an informal interview with the researcher. During the questionnaire session, researcher conducted the interview based on their most comfortable language of communication (e.g., English, Mandarin, Malay, and local Dialects). This was to ensure adequate understanding of questions and the provision of accurate information. The "Fallproof Health and Activity" questionnaire includes information such as medical information, number of falls in a year, the reasons for falls, and physical activities. All testing sessions were voice recorded for further analysis and clarification. This review process was to ensure the consistency of the interview process. After the 20-minute semi-structured interview based on material from the Fallproof Health and Activity questionnaire, participants were given a short break before the cognitive test, Mini-mental State of Examination (MMSE) adapted from Folstein et al. (1987). Participants were required to complete the tasks in 5 main areas – orientation, registration, attention and calculation, recall, language, and praxis. Lastly, the Berg Balance Scale (BBS) was administered, a scale consisting of 14 subtests performed in a standard order to measure functional abilities and balance.

In phase 2, participants were required to perform the double-limb standing balance (30-s Romberg test) and joint position sense tasks at a laboratory located at Republic Polytechnic, Singapore. The experimental design for studies III and IV is illustrated in Figure 3.

In both studies III and IV, clinical and non-clinical compression socks were assigned to the participants based on the manufacturer's sizing guidelines. To prevent carryover and order effects of the socks and barefoot, 8 different sequence orders of the treatment interventions and barefoot were created and being assigned numbers 1–8 (Table 4). Each participant was then assigned a sequence order randomly by using Microsoft Excel.

For the double-limb standing balance task in study III, participants were required to perform a 30-s Romberg test under two vision conditions (eyes open and closed) and on two standing surfaces (stable and foam). Researcher created 16 different task sequences based on the vision and standing surfaces. Each participant was then assigned a sequence order randomly by using Microsoft Excel (Table 5). Therefore, all treatment interventions and task conditions were presented in a random order for each participant.

During the 30-s double-limb standing balance task, participants were instructed to stand upright and as still as possible with feet together and the arms by the side. For the open eyes condition, participants were instructed to look straight ahead to a reference point on a blank wall, marked at eye level. The reference point position was marked about 1.5 m away from the balance platform. A thick foam pad (10 cm) was placed on top of the balance platform for the performance under the unstable surface. Before data collection, participants undertook two trials of the static balance task to familiarize themselves with each of the four task conditions – SO, SC FO, FC. For every treatment intervention, participants were required to perform 2 trials for each of the task conditions. Participants were given a sufficient rest period (~2 minutes) between each treatment intervention. The tests were repeated if participants lost balance on the platform.

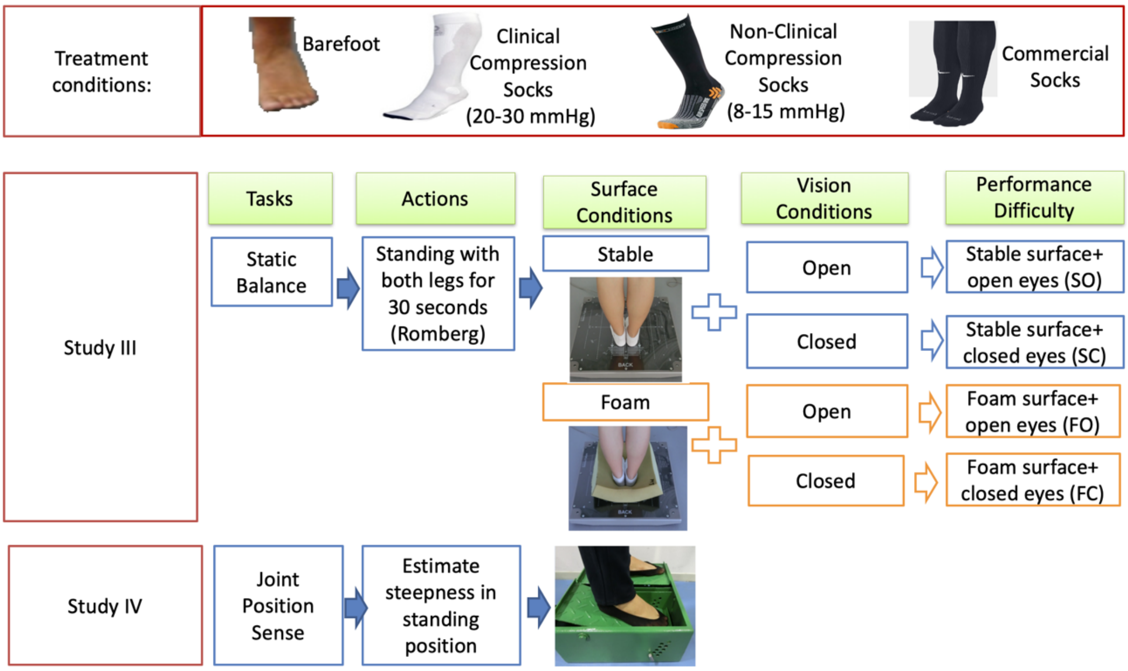


FIGURE 3 Experimental designs for studies III and IV

TABLE 4 Sequence order number for the treatment conditions

Sequence order 1: Bare > CC > NCC > NC	**Sequence order 2:** CC > NCC > NC > Bare	**Sequence order 3:** NC > Bare > CC > NCC	**Sequence order 4:** NCC > CC > NC > Bare
Sequence order 5: Bare > NC > CC > NCC	**Sequence order 6:** CC > Bare > NC > NCC	**Sequence order 7:** NC > CC > NCC > Bare	**Sequence order 8:** NCC > NC > Bare > CC

TABLE 5 Sequence order number for the task conditions

Sequence order 1 SO > SC > FC> FO	**Sequence order 2** SO > FO > SC > FC	**Sequence order 3** SO > FC > SC > FO	**Sequence order 4** SO > FO > FC > SC
Sequence order 5 SC > SO > FC> FO	**Sequence order 6** SC > FC > FO > SO	**Sequence order 7** SC > FO > FC > SO	**Sequence order 8** SC > FO > SO > FC
Sequence order 9 FO > FC > SC> SO	**Sequence order 10** FO > SO > SC > FC	**Sequence order 11** FO > FC > SO > SC	**Sequence order 12** FO > SO > FC > SC
Sequence order 13 FC > SO > SC> FO	**Sequence order 14** FC > SC > FO > SO	**Sequence order 15** FC > FO > SC > SO	**Sequence order 16** FC > FO > SO > SC

For the joint position sense awareness test, the 8 levels of steepness were assigned a number label from 1 to 8, where 1 corresponded to 2.5° and 8 to 20°. These numbers were used during the actual testing. This method was used due to low education levels and lack of understanding of the concepts of angles in this group of participants. Participants were instructed to stand vertically with zero-degree flexion at the knee and place their body weight on slope box to feel each position by using the dominant foot. During the sensing of the slope, participants were asked to look directly in front and refrained from any eye contact to the modified slope box.

Prior to actual testing, participants were asked to go through the familiarisation process of the task. A 1-minute familiarisation on each level of steepness was given to participants to sense and familiarise with the slopes. During the familiarisation, participants were informed to remember each assigned number that represented each level of steepness. For every slope, researcher constantly reminded the participants of the steepness of the surface slopes (assigned numbers) while they were sensing and remembering the surface slope. During the actual test, participants were informed that an assigned number (surface slope angles) might be repeated more than once during each treatment although that did not happen. Researcher would then randomly adjust the slope box to various levels of steepness until all levels of steepness had completed. Participants were asked to indicate the perceived level of steepness, by indicating the assigned number, when researcher presented him/her the randomly the selected target position. The same process would then repeat for the second trial. Participants were allowed to hold on the railing beside them for stability. About 2 minutes rest period between each treatment were given to participants.

4.6 Measurements (Study II, III & IV)

4.6.1 Mini-Mental State Examination

The MMSE test was used to assess the severity of cognitive impairment and cognitive changes occurring over time in older adults. There were three categories of cognitive function levels - no cognitive impairment (24–30), mild cognitive impairment (18–23), and severe cognitive impairment (0–17).

4.6.2 Berg-Balance Scale

Berg balance scale consisting of 14 subtests, with each subtest scores ranging from 0–4. Participants were required to perform in a standard order to measure functional abilities and balance. The maximum score for this assessment is 56. The categories were low risk of falling (41–56) and increased risk of falling (≤ 40).

4.6.3 Double-limb standing (30-s Romberg test)

For the double-limb standing, the sampling frequency was set at 100Hz to collect centre of pressure. Therefore, a total of 3000 data points for each condition were collected and analysed. The stabilometric parameters were the 90% confidence elliptical area (C90 sway area), trace length (TL, the total length of the CoP path), sway velocity, range of AP and ML CoP displacement, AP and ML SD. Observed increases in value of these parameters were associated with a greater risk of falling (Melzer et al., 2010).

4.6.4 Joint position sense

The absolute error value was positive whether the error was under- or over-estimation of the target position. This measure indicated the precision of estimates. The constant error value refers to the direction of position errors from the target position, a positive value for overestimation and negative for underestimation. Constant error was used to measure the direction of imprecision.

4.7 Statistical analysis (Study II, III & IV)

The Statistical Programme for Social Sciences (version 22.0 & version 24.0) was used for statistical analysis. In study II, between-group differences in mean change were analyzed by using a non-parametric test: Friedman's test for outcome measures such as MMSE and BBS scores. Post hoc testing was performed using a Wilcoxon signed-rank test when Friedman's ANOVA analysis resulted in a statistically significant outcome (alpha value set at $p < 0.05$). Results were reported as means ± standard deviation (SD) for the descriptive data; z-score (z) and Wilcoxon (W) for the Mann-Whitney (U) test. Odds ratios of risk factors associated with falls were analyzed by using Binary logistic regression. In the three age categories, Spearman's Correlation test was used to identify the correlations between MMSE and BBS scores.

In study III, the stabilometric related data was analyzed by using nonparametric statistical tests due to abnormal data distributions. All measurements across the treatment interventions were compared using a Friedman test: K related samples. If statistically significant results were found during Friedman test, Wilcoxon sign test was conducted to further identify which treatment intervention resulted in a significant effect. Results were reported as means and SD. Alpha level was set at < 0.05 for all statistical analyses.

In study IV, Cronbach's Alpha coefficient was used to check the reliability of the joint position sense test for the three treatment conditions, with barefoot condition served as the baseline, across the surface slopes tested. A value of 0.7 to 0.8 is an acceptable value for Cronbach's Alpha (Field, 2009). A mixed-model Analysis of Variance (ANOVA) with one between-groups factor of gender (male, female) and two within-participant factors on treatments and levels of surface slopes. The main effect of treatment conditions was corrected using a Bonferroni adjustment. Effect sizes of the independent variables were expressed using partial eta squared, with an effect size of 0.00099 considered to be small, an effect size of 0.0588 considered to be medium, and an effect size of > 0.1379 considered to be large (Richardson, 2011). Alpha level was set at < 0.05 for all statistical analyses.

5 RESULTS

5.1 Systematic Review and Meta-analysis (Study I)

The process of the literature review search is presented in Figure 4. A total of 66 studies were identified, 8 studies excluded after title and abstract review. From the full-text articles review process, 9 studies were excluded further as the intervention treatments, or the measure outcomes did not match the inclusion criteria. Therefore, a total of 49 studies (Appendix 5) were eligible and included for qualitative synthesis and 28 studies for quantitative synthesis. Qualitative analysis shows that the research participants of the published articles were young adults, middle-aged and older adults, and lower-limb injured individuals. Double-limb standing (DLS) balance task was the most commonly used task in the previous studies for all the three groups of lower-limb stimulation strategies. The single-leg standing (SLS) balance task as an assessment task was common in WGSS (n = 7) and SRSS (n = 6). Nevertheless, it was rarely used as the main assessment task in TMSS (n = 1) research. It was observed that a majority of the studies in WGSS and SRSS examined only one task, while the TMSS grouping tended to include two or more tasks in a single study.

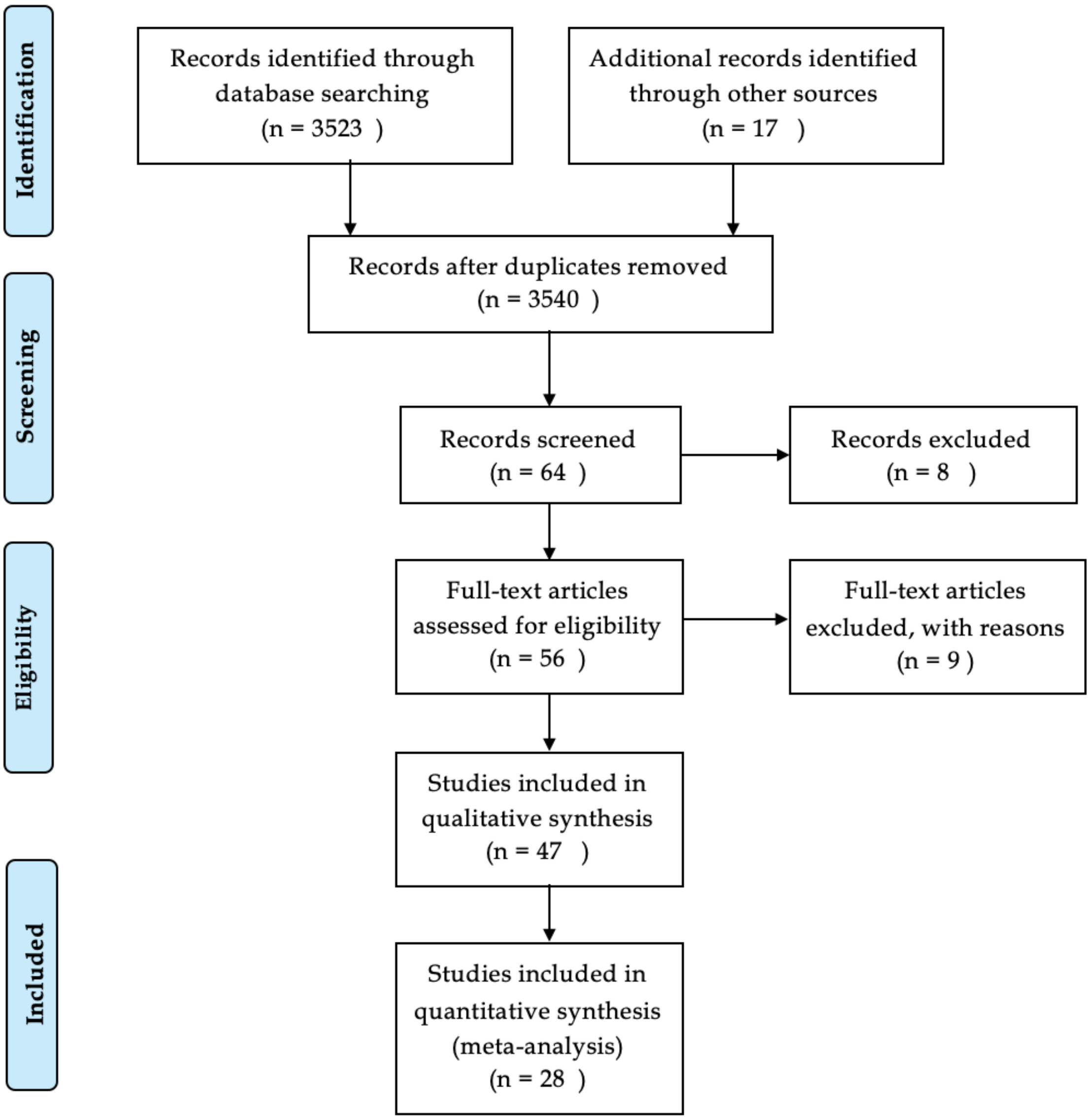


FIGURE 4 Summary of the search strategy and selection process of the included studies based on PRISMA model

5.1.1 Risk of bias

The methodological quality assessment found that high risks of bias for selection bias, performance, and detection categories were mostly found in WGSS and TMSS groupings (Figure 5). Most studies in the WGSS group were at high risk of bias for sequence generation (n = 18) and the allocation concealment category (n = 13), where most did not describe the randomization process of assigning the interventions to participants. Furthermore, most studies in the WGSS group used a non-random approach for selection of participants (High risk of bias).

In contrast, most studies (~75.5%) were at as low risk of bias in the participant attrition and reporting categories, with no missing outcome data, with all the relevant dependent variables reported. Nevertheless, there were four studies at high risk of bias for incomplete outcome data category. The reasons were: imbalanced numbers of participants across the groups (Hijmans et al., 2009; Perry et al., 2008) or because participants were excluded due to an additional injury (Palm et al., 2012) or reduced total sample sizes due to data corruption (Hatton et al., 2012).

For the outcome reporting category, 8 studies were rated at a high risk of reporting bias. These studies failed to report the key outcomes or provided incomplete information on dependent variables. The reasons for this were due to incomplete outcomes reported (Michael et al., 2014; Qiu et al., 2012; Sperlich et al., 2013) and failure to include results for key outcomes (Corbin et al., 2007; Ozer et al., 2009; Perry et al., 2008; Ross, Scott E., 2007; Sperlich et al., 2013).

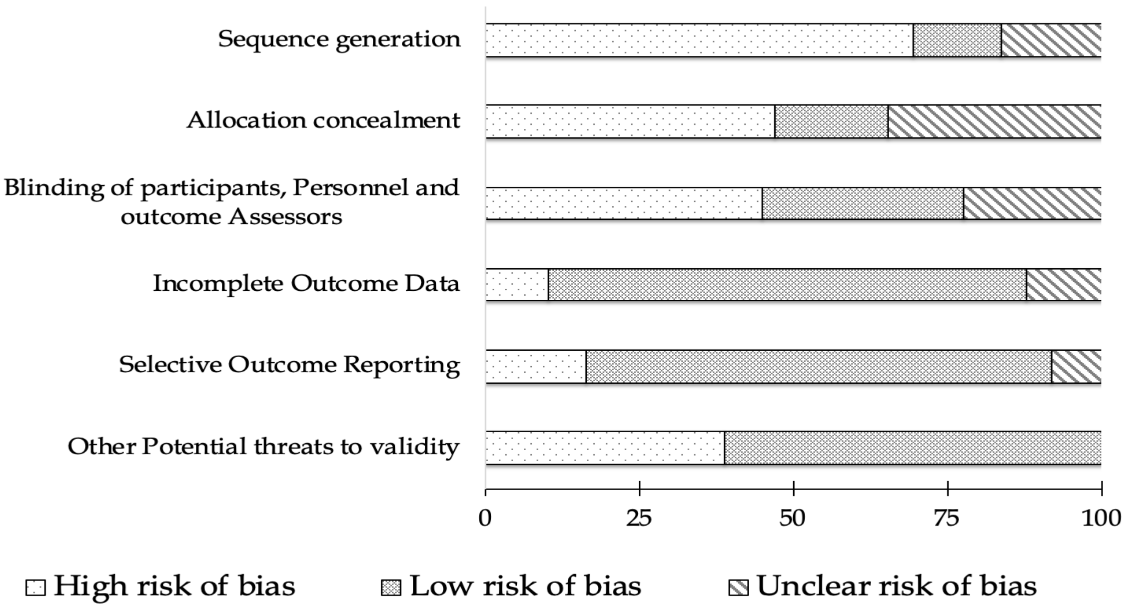


FIGURE 5 Risk of bias summary

5.1.2 Qualitative synthesis

Wearable garments stimulation strategy (WGSS). Figure 6 shows a summary of the 18 studies examining the effects of wearable garment lower-limb stimulation strategy. A total of 8 studies found that wearable garment such as braces, tapes and compression sleeves improved standing and dynamic balance tasks in participants with lower-limb injuries (n = 6), young adults (n = 2) and athlete (n = 1).

Of 7 studies, there was only one study by Gribble et al. (2010) reporting that an ankle brace did not affect the balance performance in a population with a lower-limb injury (Gribble et al., 2010). In contrast, 11 studies involved young and healthy adults (n = 8), athlete (n = 1) and middle-age and older adults (n = 2) as participants did not show beneficial effects of wearing the wearable garments.

It was observed that less than 50% of WGSS studies improved balance during single-leg standing balance task (n = 3/8; 37.5%), double-limbs standing balance task (n = 3/7; 42.9%), and dynamic balance task (n = 3/7; 42.9%).

Textured materials stimulation strategy (TMSS). Figure 7 shows a summary of the 19 studies examining the effects of textured materials lower-limb stimulation strategy. A total of 6 studies found that textured materials such as textured insoles, spike insoles, and Velcro improved standing and dynamic balance tasks in young adults. Approximately 66.7% (n = 8/12) of the studies found that TMSS enhances the performance on DLS, dynamic balance, and gait tasks in middle-age and older adults. For the neuropathy patients, 75% (n = 3/4) of the studies found the beneficial effects of using TMSS.

Six studies showed that TMSS did not benefit young adults in postural regulation during double-limb standing (n = 2) and in gait (n = 4) in young adults. Three studies found no significant improvement or detrimental effects of using textured insoles on postural regulation during the double-limb standing tasks in middle-aged and older adults.

A unique study by Menz et al. (2006) examined the effects of using Velcro to provide stimulation by rubbing gently against the skin on the side of the ankle, calf, and knee (Menz et al., 2006). The findings showed a significant reduction in postural sway in young and healthy adults, older adults, and diabetic peripheral neuropathy patients

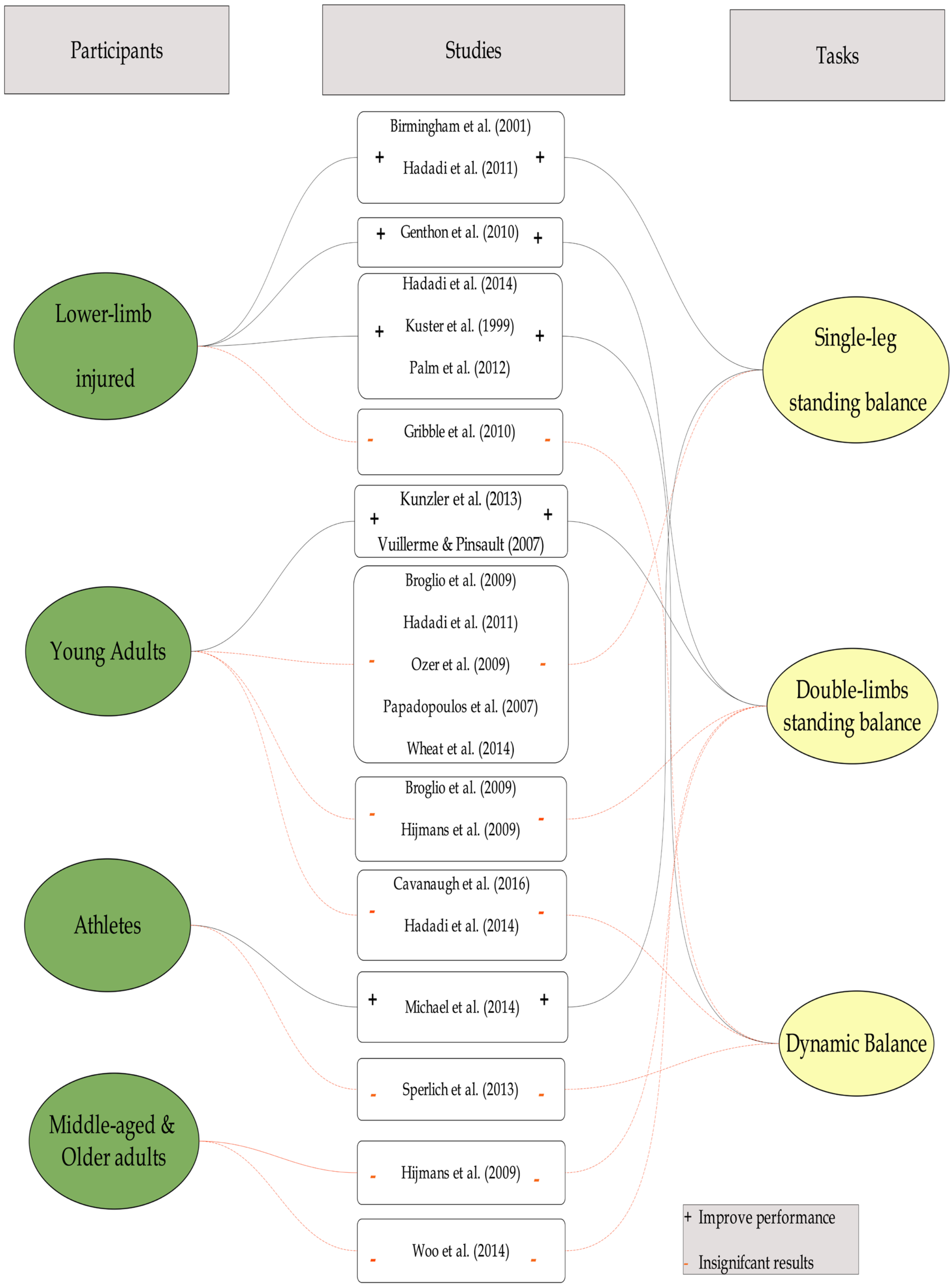


FIGURE 6 A summary of WGSS studies

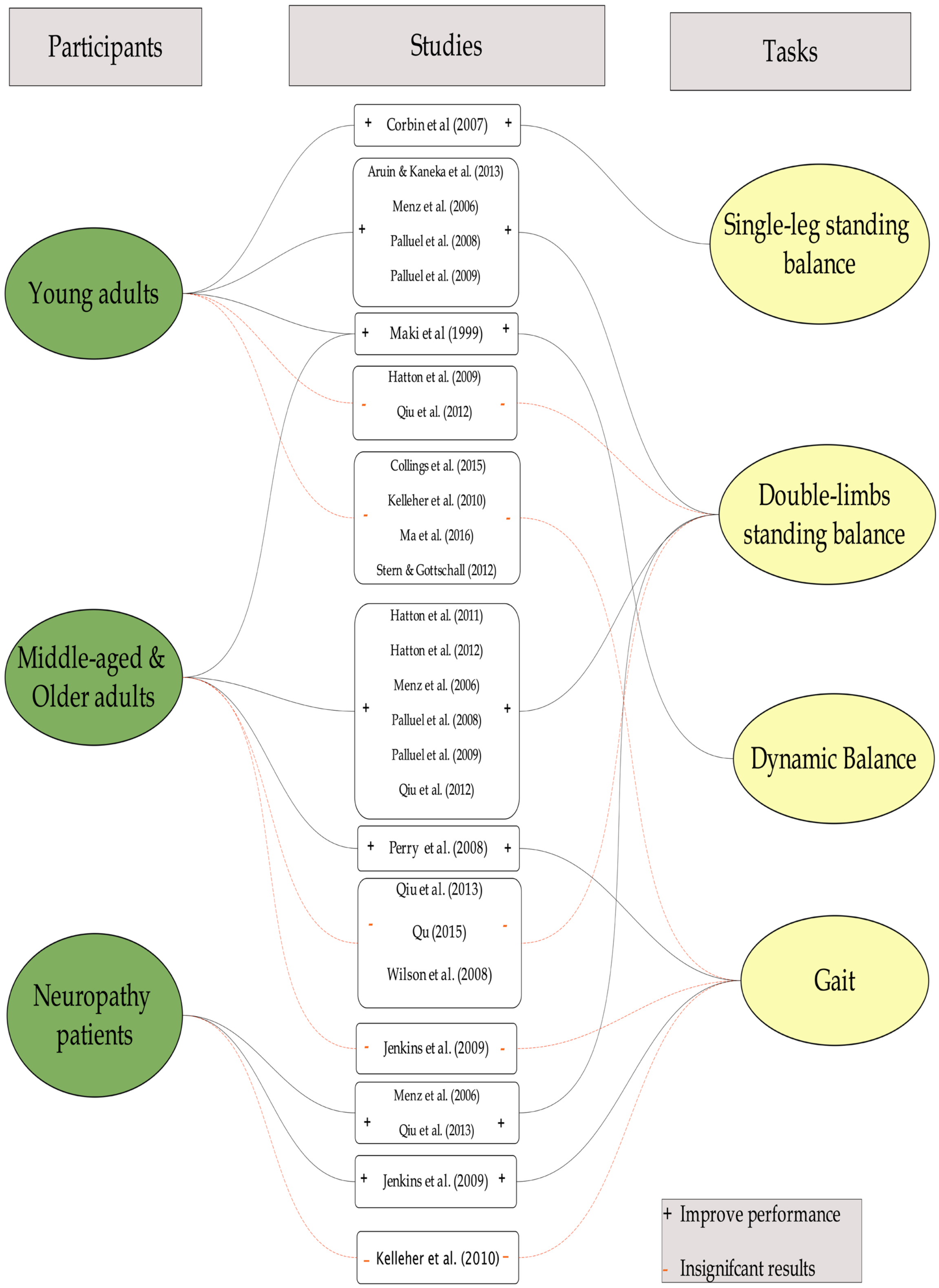


FIGURE 7 A summary of TMSS studies

Application of Stochastic Resonance stimulation strategy (SRSS). Figure 8 shows a summary of the 11 studies examining the effects of an application of Stochastic Resonance lower-limb stimulation strategy. Majority of the studies (83.3%) showed an application of SR improved the performance of all balance tasks in participants with lower-limb injuries (n = 3), young adults (n = 5), and older participants (n = 2). 8 studies found positive effects of applying SRSS in SLS and DLS balance tasks.

Collins et al. (2012) was the only study that did not find a significant improvement in performance on a single-leg standing task in older adults and participants with knee osteoarthritis condition (Collins et al., 2012). Similarly, Ross and Guskiewicz (2006)'s finding did not find a significant improvement in dynamic balance task for both the young adults and lower-limb injuries participants (Rose & Guskiewicz 2006).

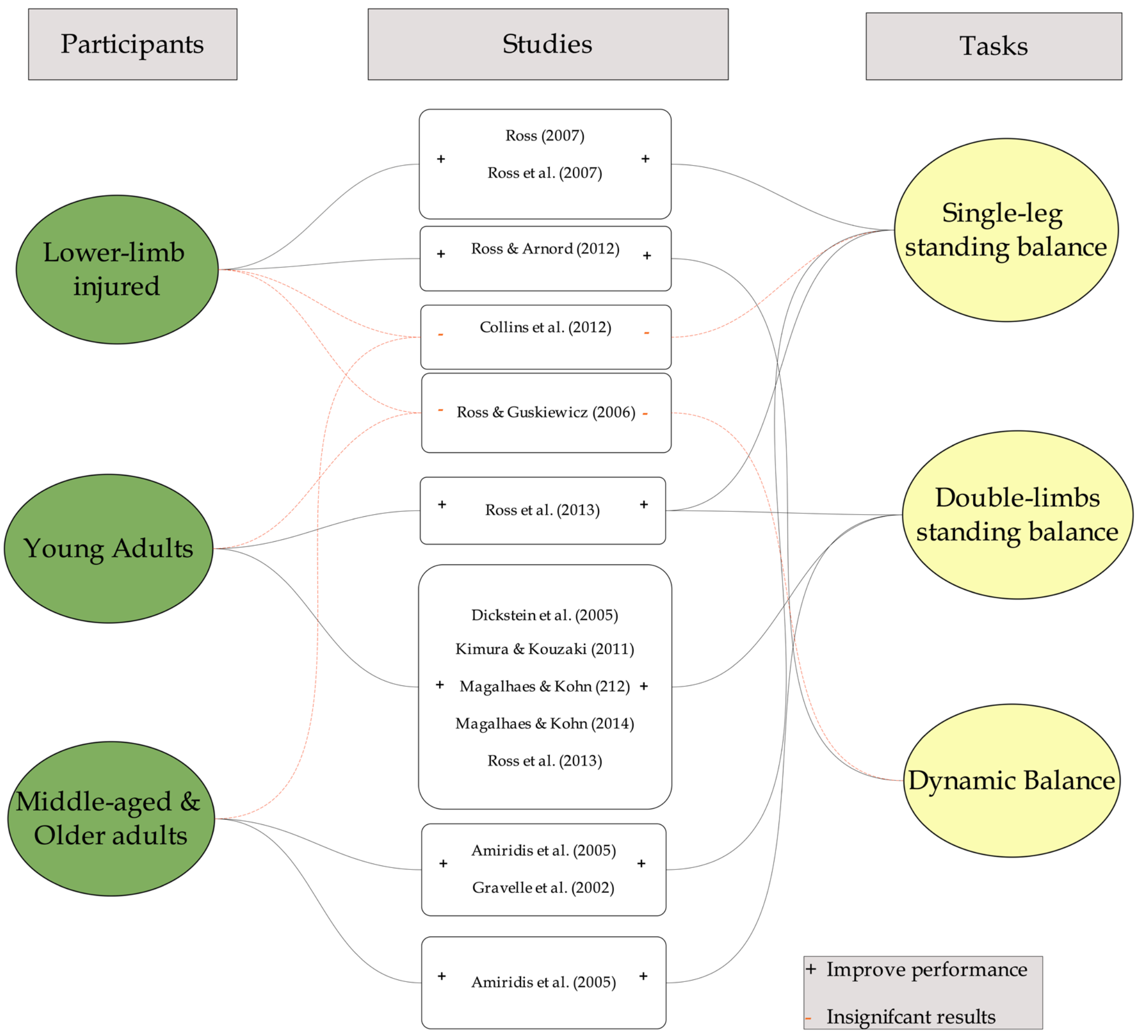


FIGURE 8 A summary of SRSS studies

5.1.3 Quantitative analysis

A total of 28 studies were included in the meta-analysis as they reported CoP measurement outcomes for the static balance tasks: SLS and DLS. The three sub-groups of lower-limbs stimulation strategies were wearable garments (n = 10), textured materials (n = 10) and application of SR (n = 8). The participants were categorized into young adults, older adults, and lower limbs injured individuals. Single-leg standing and double-limbs standing were the two main tasks included in the meta-analysis. Figure 9 illustrates the mean Unbiased (Hedges' g) standardized mean differences (SMD) of the three lower-limb sensory stimulation strategies categories: stochastic resonance, wearable garments, and textured material.

Participants: Young adults, older adults and lower-limb injuries individuals. A total of 16 studies (WGSS = 6; TMSS = 6; SRSS = 4) that involved young adults were included in the analysis. Mean SMD of SRSS was the highest among the three categories (Figure 10). An overall positive effect of applying SRSS were observed during performance of static balance tasks on a stable surface (Z = 2.95, p = 0.003). In contrast, WGSS shows no positive effect (SMD = 0.00) and a low effect was observed in TMSS (SMD = 0.26). There was evidence of moderate heterogeneity for TMSS (Tau^2 = 0.10; df = 5; I^2 = 62%) and SRSS (Tau^2 = 0.12; df = 3; I^2 = 67%) but low heterogeneity was found in WGSS (Tau^2 = 0.04; df = 5; I^2 = 38%).

For the older adults, it showed a high negative effect of WGSS (SMD = -0.68) which infers a positive capacity of the control group in regulating the posture during the static balance tasks. The pooled effect size for TMSS and SRSS appeared low (SMD = 0.30 and 0.31 respectively). There was evidence of moderate heterogeneity for WGSS (Tau^2 = 0.41; df = 1; I^2 = 69%), TMSS (Tau^2 = 0.09; df = 6; I^2 = 61%) and SRSS (Tau^2 = 0.10; df = 2; I^2 = 67%).

For the lower-limb injured individuals, the pooled effect size values were low and moderate in WGSS (SMD = 0.20, Z = 1.54, p = 0.12) and SRSS (SMD = 0.41, Z = 1.75, p = 0.08) sub-groups, respectively.

Tasks: Single-leg standing (SLS) and Double-limbs standing (DLS). Five studies each from WGSS and SRSS reported CoP related parameters of postural regulation during the performance of the SLS task. There was a significant difference between the two subgroups, WGSS and SRSS (p = 0.02), where a higher pooled effect size was observed in SRSS group (SMD = 0.49, Z = 2.40, p = 0.02). There was a high level of heterogeneity observed in the SRSS (Tau^2 = 0.15; df = 4; I^2 = 76%) group compared to the homogeneity observed in the WGSS group (Tau^2 < 0.01; df = 4; I^2 = 0%). This finding indicated that 76% of the variability between effect sizes of SRSS studies displayed a systematic influence of one or more variables. The average pooled effect size for the WGSS was found to be 0.20, which corresponds to a small effect size. In comparison, the SRSS had a moderate effect size (SMD = 0.41). The overall application of both WGSS and SRSS during SLS had beneficial effects on postural regulation during performance of a SLS task on stable surfaces with eyes open and closed condition (Z = 1.92, p = 0.05).

For the DLS balancing task, a total of 20 studies (WGSS = 5; TMSS = 10; SRSS = 5) were included for analysis. Low to moderate mean effect sizes were found on the implementation of TMSS (SMD = 0.29) and SRSS (SMD = 0.55) on performance in the DLS balance task. In contrast, the WGSS (SMD = 0.05) barely showed any effects on postural regulation measurements during the DLS balance task. A significant level of heterogeneity was observed in all three lower-limb stimulation strategies, suggesting that different population samples, vision and surface conditions, or experimental design-related factors influenced levels of variability across effect sizes. The findings showed beneficial effects when applying all three lower-limb stimulation strategies during the performance in the DLS task on stable surfaces (Z = 2.91, p = 0.004).

Our findings showed that the SRSS is more effective compared to TMSS and WGSS under the SLS and DLS conditions.

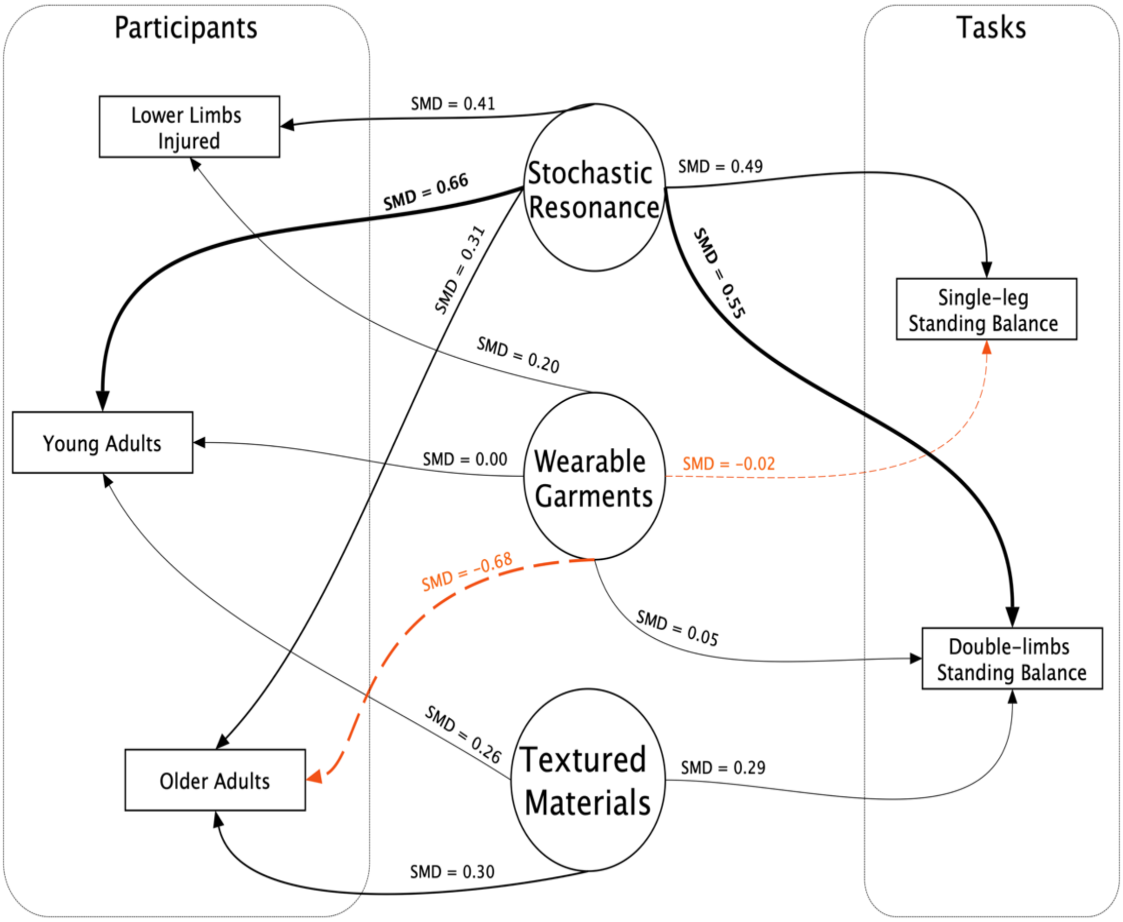


FIGURE 9 Unbiased (Hedges' g) standardized mean differences (SMD) in the three categories of lower-limbs stimulation strategies

5.2 Participants' Socio-demographic characteristics (Study II, III & IV)

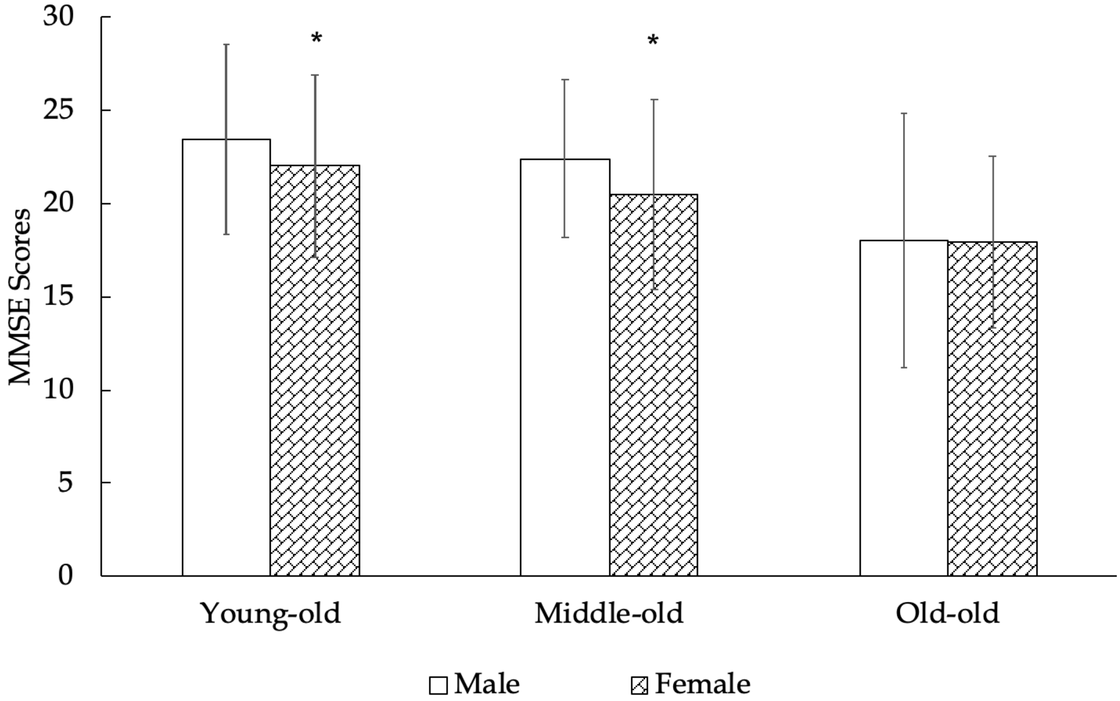
The distribution of the elderly individuals according to gender was as follows: 63.9% (n = 246) were women and 36.1% (n = 139) were men. Of the 385 participants, 69.9% were Chinese, 26.2% were Malay, 3.1% were Indian, and 0.8% were others. A total of 107 (27.8%) elderly individuals experience at least 1 fall in the past 1 year. The percentage of falling was higher in the oldest-old group. For the education levels, it was found that 79.5% of the elderly individuals received less than 6 years of education. From the medical condition perspective, it was noted that hypertension and high cholesterol were the two common medical conditions faced by elderly individuals.

5.2.1 Cognitive and balance abilities

Based on the MMSE scores, the overall mean score was significantly higher in male (23.4 ± 5.1) compare to female (22.0 ± 4.9) participants (U = 13560.50, W = 43941.5, Z = -3.379, $p < 0.05$). Significant results were also observed for male participant in the young-old (U = 4335.50, W = 12981.5, Z = -2.241, $p < 0.05$) and middle-old (U = 1921.00, W = 6386.0, Z = -2.143 $p < 0.05$) groups (Figure 10).

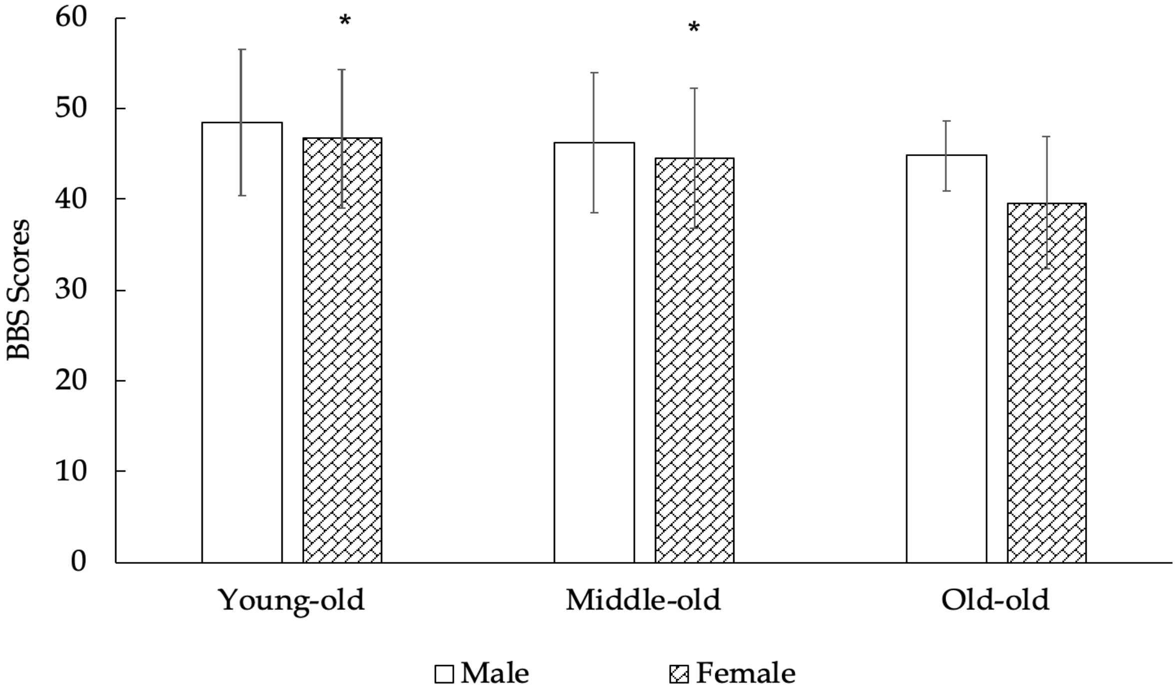
For the balance ability, the male participants displayed significantly higher scores (47.5 ± 7.9) compare to female (45.2 ± 7.8) participants (U = 13459.5, W = 43840.5, Z = -3.473, $p < 0.05$). A significant result was observed in the young-old (U = 4220.50, W = 12866.5, Z = -2.505, $p < 0.05$) group whereby the score was significantly higher in male participants (Figure 11).

The spearman correlation test values shows moderate relationship between the MMSE and BBS scores in young-old ($r = 0.467$, $p < 0.001$) and medium-old ($r = 0.502$, $p < 0.001$) groups.



* Significantly lower than male

FIGURE 10 Mini-mental state examination scores according to the three age groups in male and female



* Significantly lower than male

FIGURE 11 The scores of Berg balance test according to the three age groups in male and female

5.2.2 Risk factors for falls and cognitive impairment

From the binary logistic regression, it was shown that mild cognitive impairment (OR: 1.874) and Berg Balance scale scores at and below the cut-off of 40 (OR: 0.25) are the main risk factors for falls.

5.3 Double-limb standing (30-s Romberg test) (Study III)

5.3.1 Postural sway (c90) area

The comparisons of sway area (c90), trace length and sway velocity across the treatment interventions of the four levels of performance difficulty is shown in Table 6. For the female group performed on the foam surface with eyes open (FO), the Friedman test showed significant differences across the treatment interventions ($\chi 2$ (3) = 12.092, $p < 0.05$) ($p = 0.007$) (Table 6). In comparison with the barefoot condition, Post hoc analysis showed that female participants wearing the NCC (z = -2.484, $p < 0.05$) and NC (Z = -2.403 $p < 0.05$) KLS significantly reduce the sway area. Nevertheless, no statistically significant differences were found across the treatment interventions in men.

TABLE 6 Postural sway C90 area (mm²) across the treatment interventions of four different performance difficulties in older men and women (Mean ± SD)

a. Men (N = 23)					
	Clinical level compression	**Non-clinical level compression**	**Non-compression**	**Barefoot**	**p-value**
Stable Surface with Eyes Open (SO)	484.0 ± 166.8	456.9 ± 168.0	448.9 ± 199.3	427.9 ± 156.9	> 0.05
Form Surface with Eyes Open (FO)	778.2 ± 376.2	790.4 ± 430.4	853.9 ± 483.3	823.1 ± 337.2	> 0.05
Stable Surface with Closed Eyes (SC)	858.7 ± 312.8	876.46 ± 470.9	860.3 ± 366.0	792.93 ± 336.0	> 0.05
Foam Surface with Closed Eyes (FC)	1610.4 ± 591.8	1553.1 ± 656.0	1784.0 ± 830.9	1442.1 ± 468.8	> 0.05

b. Women (N = 23)					
	Clinical level compression	**Non-clinical level compression**	**Non-compression**	**Barefoot**	**p-value**
Stable Surface with Eyes Open (SO)	418.1 ± 220.0	462.2 ± 260.3	447.9 ± 171.8	497.2 ± 302.5	> 0.05
Form Surface with Eyes Open (FO)	655.5 ± 338.7	617.7 ± 330.7*	643.3 ± 351.3*	776.6 ± 564.2	< 0.05
Stable Surface with Closed Eyes (SC)	734.8 ± 394.9	767.46 ± 637.2	636.1 ± 275.9	798.78 ± 488.0	> 0.05
Foam Surface with Closed Eyes (FC)	1227.3 ± 659.3	1292.1 ± 688.1	1384.7 ± 786.2	1479.7 ±1172.7	> 0.05

* Significantly lower than barefoot

5.3.2 Trace length

The comparison of trace length across the treatment interventions of the four levels of performance difficulty is shown in Table 7. The Friedman test revealed significant differences across the treatment interventions on the foam surface with eyes open ($\chi 2$ (3) = 8.607, $p < 0.05$) in women. In contrast, no statistical differences were found in the other three task conditions; SO, SC and FC. From the Post hoc analysis, it showed that trace length was significantly shorter while participants wore the NCC KLS (Z = -2.321, $p < 0.05$), compared to the barefoot condition for the FO task condition. In contrast, no statistically significant effects were found across the treatment interventions in men.

TABLE 7 Trace length (mm) across the treatment interventions of four different performance difficulty in older men and women (Mean ± SD)

a. Men (N = 23)

	Clinical level compression	Non-clinical level compression	Non-compression	Barefoot	p-value
Stable Surface with Eyes Open (SO)	601.6 ± 150.7	576.6 ± 220.5	587.3 ± 220.1	562.3 ± 155.2	> 0.05
Form Surface with Eyes Open (FO)	697.9 ± 183.2	737.9 ± 283.5	679.2 ± 175.6	720.0 ± 220.5	> 0.05
Stable Surface with Closed Eyes (SC)	884.5 ± 287.2	908.5 ± 407.9	914.6 ± 392.7	885.9 ± 335.5	> 0.05
Foam Surface with Closed Eyes (FC)	1141.2 ± 379.0	1064.4 ± 358.2	1116.5 ± 323.9	1107.7 ± 310.5	> 0.05

b. Women (N = 23)

	Clinical level compression	Non-clinical level compression	Non-compression	Barefoot	p-value
Stable Surface with Eyes Open (SO)	418.1 ± 220.0	462.2 ± 260.3	500 ± 151.1	525.7 ± 198.1	> 0.05
Form Surface with Eyes Open (FO)	614.9 ± 158.4	592.6 ± 146.3*	610.1 ± 169.0	629.6 ± 187.7	< 0.05
Stable Surface with Closed Eyes (SC)	668.2 ± 241.5	687.6 ± 280.8	651.71 ± 208.8	690.5 ± 262.7	> 0.05
Foam Surface with Closed Eyes (FC)	881.6 ± 211.9	906.7 ± 235.2	907.3 ± 243.2	907.6 ± 250.9	> 0.05

* Significantly lower than barefoot

5.3.3 Sway velocity

The comparisons of sway velocity across the treatment interventions of the four levels of performance difficulty are shown in Table 8. For the FO task condition, the Friedman test revealed significant differences across the treatment interventions ($\chi2$ (3) = 9.209, $p < 0.05$) in women. Post hoc analysis showed that sway velocity was significantly lower while wearing the CC (Z = -2.038, $p < 0.05$) and NCC KLS (Z = -2.494, $p < 0.05$) compared to the barefoot condition. In contrast, no statistically significant effects were found across the treatment interventions in men.

TABLE 8 Sway velocity (mm/s) across the treatment interventions of four different performance difficulty in older men and women (Mean ± SD)

a. Men (N = 23)

	Clinical level compression	Non-clinical level compression	Non-compression	Barefoot	p-value
Stable Surface with Eyes Open (SO)	19.8 ± 5.4	19.2 ± 7.4	19.5 ± 7.3	18.7 ± 5.2	> 0.05
Form Surface with Eyes Open (FO)	23.3 ± 6.11	24.6 ± 9.5	22.6 ± 5.9	24.4 ± 7.3	> 0.05
Stable Surface with Closed Eyes (SC)	29.5 ± 9.6	30.28 ± 13.6	30.08 ± 12.7	29.53 ± 11.2	> 0.05
Foam Surface with Closed Eyes (FC)	38.0 ± 12.6	36.4 ± 11.2	37.1 ± 10.9	36.9 ± 10.4	> 0.05

b. Women (N = 23)

	Clinical level compression	Non-clinical level compression	Non-compression	Barefoot	p-value
Stable Surface with Eyes Open (SO)	16.3 ± 4.5	17.1 ± 5.3	16.7 ± 5.0	17.4 ± 6.7	> 0.05
Form Surface with Eyes Open (FO)	20.3 ± 5.1*	20.1 ± 5.1*	20.0 ± 5.2	21.4 ± 6.0	< 0.05
Stable Surface with Closed Eyes (SC)	22.9 ± 7.6	22.4 ± 9.1	21.5 ± 7.1	23.1 ± 8.7	> 0.05
Foam Surface with Closed Eyes (FC)	29.5 ± 7.1	29.5 ± 7.3	30.6 ± 7.6	30.2 ± 8.4	> 0.05

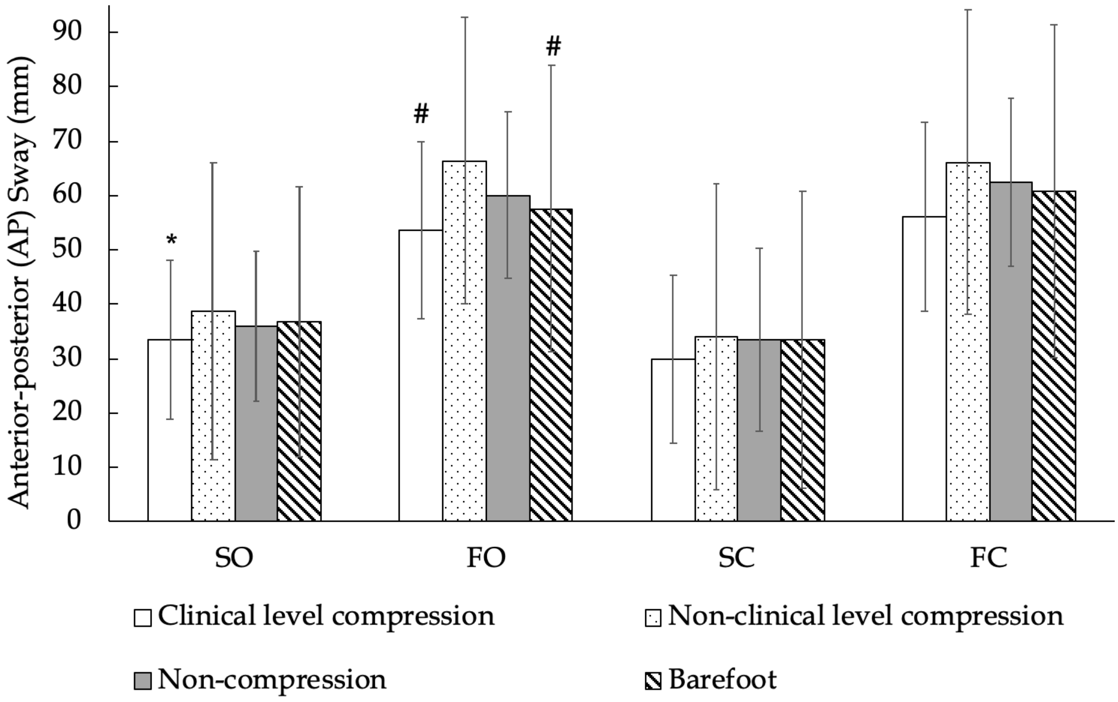
* Significantly lower than barefoot

5.3.4 Anterior-posterior postural sway and anterior-posterior standard deviation

There were significant differences across the treatment interventions in AP sway on both stable ($\chi2$ (3) = 9.052, $p < 0.05$) and foam ($\chi2$ (3) = 9.209, $p < 0.05$) surfaces, with eyes open in older men (Figure 12).

In the SO task condition, post hoc analysis revealed that CC KLS significantly decreased AP sway compared to when wearing NCC KLS (Z = -2.494, $p < 0.05$) and when standing barefoot (Z = -2.068, $p < 0.05$) in the elderly men. The same beneficial effect of wearing CC KLS (Z= -3.224, $p < 0.05$) and NCC KLS (Z = -2.403, $p < 0.05$) were observed in the FO condition.

A significant difference across treatment interventions was observed on APSD ($\chi2$ (3) = 8.896, $p < 0.05$) in the SC condition (Figure 13). Post hoc analysis revealed that NCC KLS significantly decreased APSD compared to when wearing NC KLS (Z = -2.023, $p < 0.05$. In contrast, no significant differences were found in all treatment interventions and all task conditions on AP sway and AP SD values in the women.



* Significantly lower than NCC and barefoot
\# Significantly lower than NCC

FIGURE 12 Anterior-posterior sway (mm) across the treatment interventions of four different performance difficulty in older men (Mean ± SD)

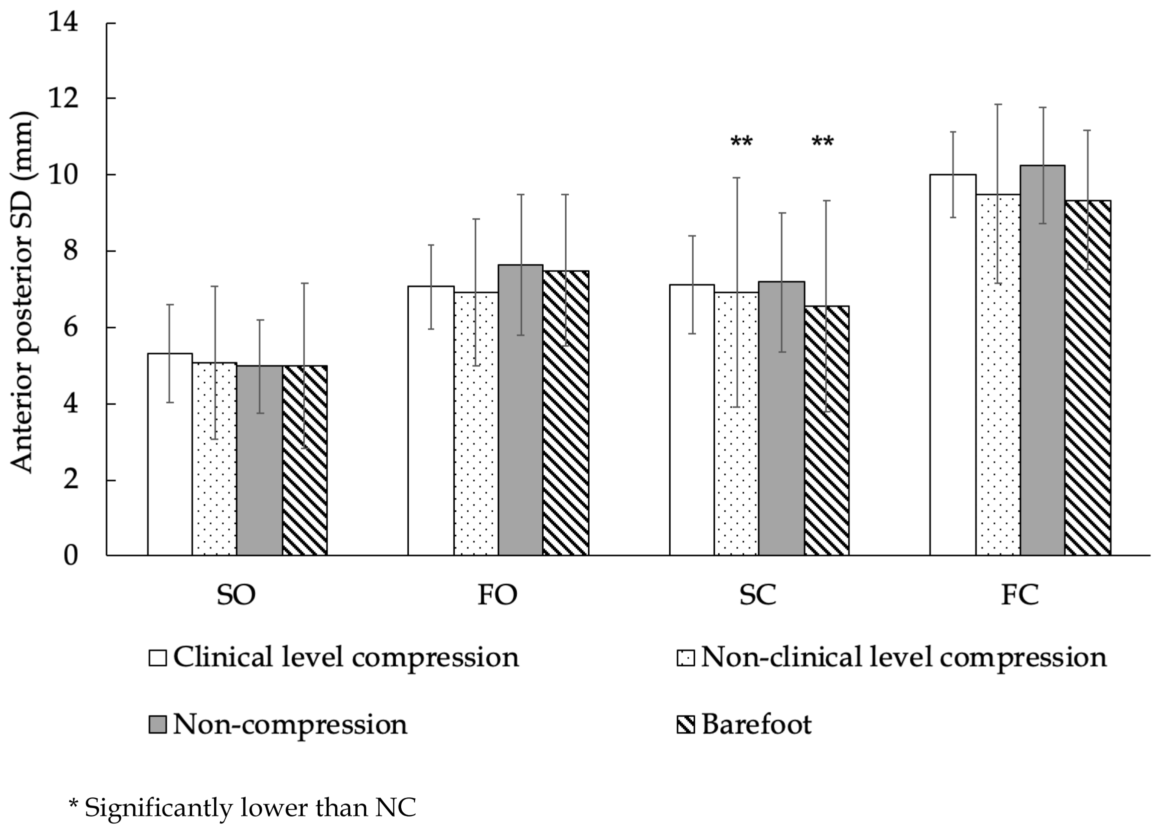


FIGURE 13 Anterior-posterior SD (mm) across the treatment interventions of four different performance difficulty in older men (Mean ± SD)

5.3.5 Medial-lateral postural sway and medial-lateral standard deviation

For the male group, there were no differences across the treatment interventions on ML sway and ML SD. In the SC task condition, a significant difference across treatment conditions was observed in MLSD ($\chi 2$ (3) = 10.092, $p < 0.05$) in the women.

5.4 Joint position sense (Study IV)

5.4.1 Reliability test

The joint position sense test for the three treatment conditions compared with barefoot had the Cronbach's alpha value at and more than 0.75, which showed good reliability.

5.4.2 Overall joint position errors

The mean absolute and constant errors of the three treatment interventions and barefoot condition are shown in Figure 14. There was a significant main effect of treatment intervention F (3, 138) = 3.219, $p < 0.05$, $\eta^2 = 0.07$ (medium effect size) in mean absolute errors. In comparison to barefoot condition, simple contrast revealed that wearing compression socks F (1, 46) = 6.869, $p < 0.05$, $\eta^2 = 0.09$ (medium effect size) and non-compression socks F (1, 46) = 4.616, $p < 0.05$, $\eta^2 = 0.13$ (medium effect size) significantly reduced the mean absolute errors.

In contrast, there was no significant main effect of treatments F (3, 138) = 2.045, $p > 0.05$, $\eta^2 = 0.04$ (low effect size) for mean constant errors. Nevertheless, simple contrast analysis revealed that wearing compression socks reduced the constant errors compared to barefoot condition F (1, 46) = 4.616, $p < 0.05$, $\eta^2 = 0.09$ (medium effect size). The results support that wearing both compression and non-compression socks reduced the overall joint position errors in the elderly population.

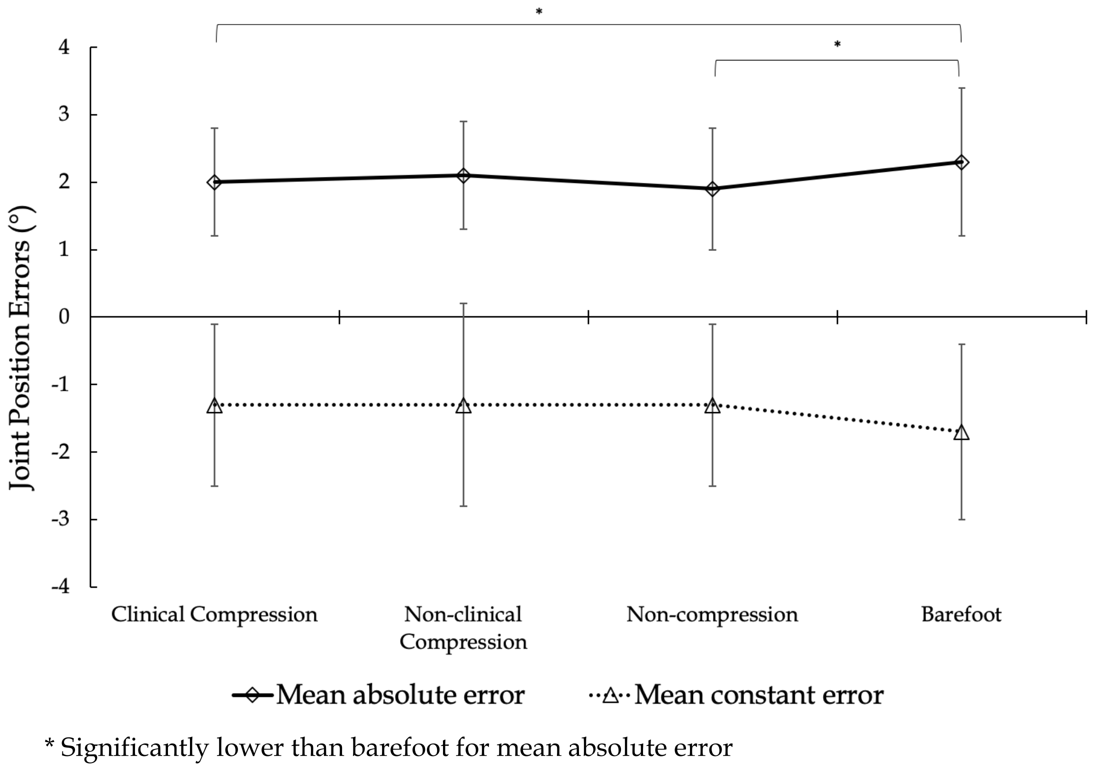


FIGURE 14 Mean (+SD) joint position errors during the four treatment conditions

5.4.3 Absolute errors across angles

The absolute errors according to the 8 levels of steepness in men and women are shown in Figure 15. There was a significant main effect of angle F (7, 322) = 82.317, $p < 0.05$, $\eta^2 = 0.64$ (large effect size). Besides the level between 15° and 17.5°, F (1, 46) = 0.984, $p > 0.05$, $\eta^2 = 0.02$, simple contrast revealed that almost all levels of steepness have significant effects on absolute errors.

There was a significant interaction between angles and treatment F (21, 966) = 2.201, $p < 0.05$, $\eta^2 = 0.05$ in men. At the 10°of steepness, the absolute errors were significantly lower while male participants wore the clinical compression F (1, 23) = 6.024, $p < 0.05$, $\eta^2 = 0.21$ (large effect size) and non-compression socks F (1, 23)

= 11.917, $p < 0.05$, $\eta^2 = 0.34$ (large effect size). At the 12.5°of steepness, both non-clinical compression F (1, 23) = 6.540, $p < 0.05$, $\eta^2 = 0.22$ (large effect size) and non-compression socks F (1, 23) = 5.793, $p < 0.05$, $\eta^2 = 0.20$ (large effect size) significantly reduced the absolute errors in men.

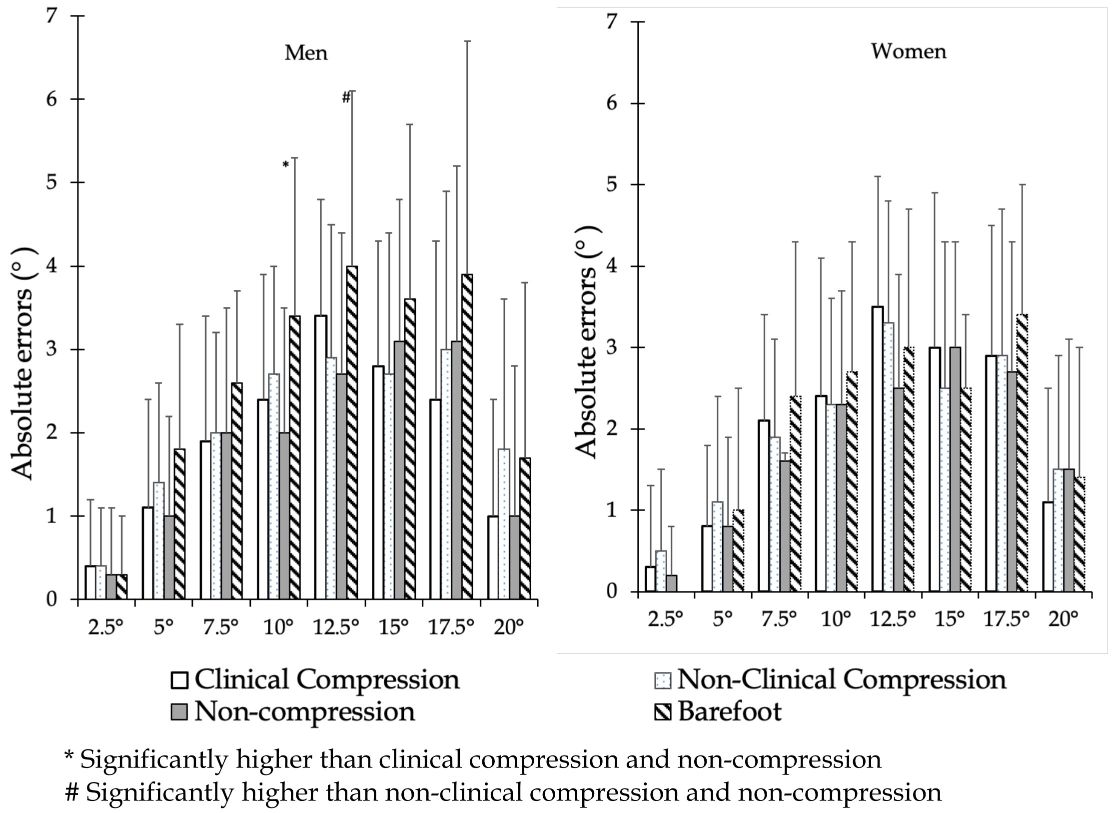


FIGURE 15 Mean (+SD) absolute errors during the four treatment conditions

5.4.4 Constant errors across angles

The constant errors according to the 8 levels of steepness in men and women are shown in Figure 16. There were no significant main effects of i) treatment interventions F (3, 138) = 2.045, $p > 0.05$, $\eta^2 = 0.04$ (low effect size), ii) interaction between treatment interventions and gender F (3, 138) = 2.631, $p = 0.05$, $\eta^2 = 0.05$ (low effect size), iii) gender F (1, 46) = 0.478, $p > 0.05$, $\eta^2 = 0.01$, and iv) treatment F (3, 138) = 2.045, p > 0.05, $\eta^2 = 0.04$.

There was a significant main effect of angle F (7, 322) = 41.022, $p < 0.05$, $\eta^2 = 0.471$ (large effect size) (Figure 4). Simple contrast analysis revealed that almost all levels of steepness have significant effects on constant errors except for the level between 7.5 and 10, F (1, 46) = 0.225, $p > 0.05$, $\eta^2 = 0.005$).

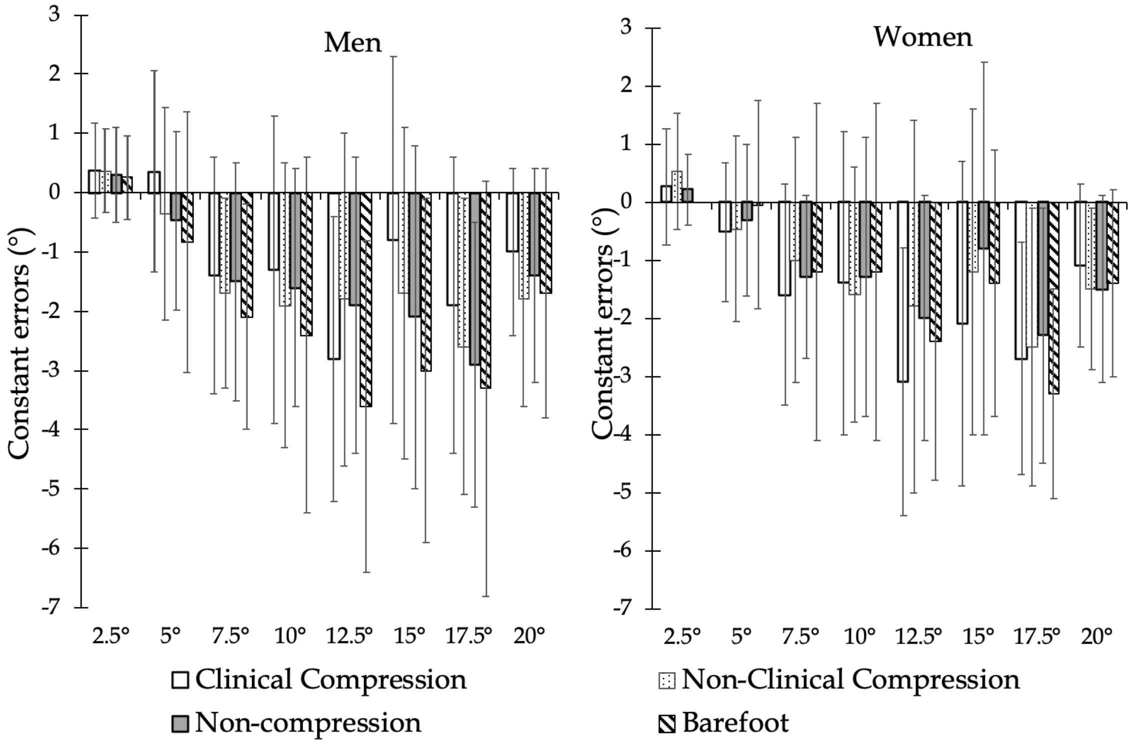


FIGURE 16 Mean (+SD) constant errors during the four treatment conditions

6 DISCUSSION

The present programme aimed to investigate the effects of lower-limb sensory stimulation strategies, specifically knee length socks of various compression levels, on somatosensory functions in community-dwelling, healthy, elderly individuals of Singapore population. The first study aimed to examine and consolidate as a review of the effects of different lower-limb sensory stimulation strategies on postural regulation and stability. The second study aimed to profile the socio-demographics and to compare the occurrence of falls, cognitive function, and balance in a sample of Singapore's elderly population. The third study aimed to find out the effects of wearing knee length socks differing in compression levels on postural regulation in community-dwelling, healthy, elderly men and women. Last, the fourth study investigated whether wearing knee-length compression socks would enhance proprioceptive feedback, providing more accurate information about feet in a group of elderly participants.

6.1 Effects of lower-limbs sensory stimulation strategies (Study I)

From our review paper, an application of Stochastic Resonance showed large positive impacts in young adults, especially during static balance standing tasks; single-leg standing and double-limbs standing. Similarly, the positive impact (moderate effects) on postural regulation was observed in older adults and lower-limb injured participants. The quantitative synthesis revealed moderate positive effects of wearing textured materials on postural regulation during static balance task. The similar observations were shown through the qualitative synthesis whereby textured materials such as insoles improved static standing balance and dynamic balance tasks in young adults, middle-aged and older adults. In contrast, quantitative synthesis revealed that wearing wearable garments did not have positive effects on static balance tasks in young participants and older adults.

For the experimental tasks, it was also observed that both SLS and DLS were the popular experimental paradigms used in most of the included studies. The possible reason for their popularity could be due to the complex sensory information perceptual mechanisms used during upright stance. Another reason could also due to the association between DLS and the risk of falling, especially in the elderly population (Lajoie & Gallagher, 2004; Rose, 2010). For a comparative examination of balance performance between the injured and non-injured legs, single-leg standing balance task was used to increase the task difficulty in the included studies (Birmingham et al., 2001; Collins et al., 2012; Hadadi et al., 2011; Ross et al., 2007; Ross, 2007; Ross et al., 2013).

The majority of the studies in the WGSS grouping were targeting the joint receptors by applying wearable garments at the ankle joint. The cutaneous receptors at the soles of the feet were the most common stimulation sites used in TMSS studies. The site of stimulation used in the SRSS research was typically between the knee and the shank, targeting m0uscle spindles and mechanoreceptors. The review found moderate to high effect sizes of applying Stochastic Resonance, investigators might want to consider sites of stimulation (e.g., knee and shank) in future WGSS and TMSS studies.

6.1.1 Wearable garments

In this review, we found that most studies used a non-random approach for selection of participants, which put all these studies under the category of high risk of bias. The non-random approach in selecting participants is likely to create a systematic error, and this either underestimates or overestimates the results of wearable garments on postural regulation. It could be due to the high risk of bias found in WGSS studies that led to inconclusive and negative findings in most studies. It is therefore important to adopt the randomized controlled trial approach to study the effects of wearable garments in the future.

The qualitative synthesis showed that both SLS and DLS were most commonly used in studies of wearable garments. Most of the included studies focused on investigating the effects of using WRSS in young and lower limbs' injured participants. In comparison to elderly population, it is more common to have young adults to wear socks, ankle braces and compression garments. In addition, ankle sprain and knee injuries are common among the younger populations due to their involvement in sport. This could serve as a motivation for researchers to investigate the beneficial effects of WRSS on postural regulation in young adults.

We found that studies supported that wearable garments enhance the stimulation of plantar cutaneous receptors in the lower limbs, except in the elderly people (Birmingham et al., 2001; Genthon et al., 2010; Kraemer et al., 1998; Kuster et al., 1999; Vuillerme & Pinsault, 2007). Our Qualitative synthesis also showed evidences that tapes (Kunzler et al., 2013; Vuillerme & Pinsault, 2007), braces (Birmingham et al., 2001) and compression stocking (Genthon et al., 2010; Kraemer et al., 1998; Kuster et al., 1999) provide additional somatosensory information which enhances postural control during the balance tasks. Similarly, quantitative synthesis found positive effects of using wearable garments on postural control under static task constraints, especially in people with lower-limb injuries (Birmingham et al., 2001; Genthon et al., 2010; Hadadi et al., 2011; Hadadi et al., 2014; Kuster et al., 1999; Palm et al., 2012). These observation suggest that stimulation to skin receptors via tapes, braces and compression helps people with lower-limb injuries exploit the available "sensorimotor system noise". We suggest that wearable garments can be a viable intervention to ameliorate the disruptive effects of the injury on mechanoreceptor in an injured limb, by increasing the sensory stimulation of the cutaneous receptors.

Limited evidence to support the use of WGSS in improving the balance performance in young adults where only two studies showed positive effects of applying medical and athletic adhesive tapes during DLS balance tasks (Kunzler et al., 2013; Vuillerme & Pinsault, 2007). The unique point of these two studies was the stimulation location. They pasted the tapes, which was around the ankle region on the anterior aspect of the ankle (Vuillerme and Pinsault, 2017) and along the Achilles tendon (Kunzler et al., 2013). While on the contrary, the application of wearable garments was generic without targeting specific stimulation location of the lower limbs. Therefore, we suggest that ankle joint receptors in these two areas might be more sensitive and receptive to the pressure applied by the tapes. Further studies are needed to investigate the location-specific effects of worn garments on motor task performance, to evaluate this possibility.

In contrast, the quantitative synthesis showed large negative effect size of compression garments (bandage and socks) on postural regulation in older adults. The main contribution of the negative effect size was from Hijmans et al. (2009)'s study. They found a main effect of compression, with balance significantly disturbed in the elderly aged 85.4 ± 4.6 years old (Hijmans et al., 2009). Nevertheless, another study found that both compression and commercial socks displayed similar effects as seen under barefoot condition in postural regulation for the anterior-posterior (AP) and medial-lateral (ML) motions for the elderly participants aged 70.9 ± 5.9 years old. The main difference between these two studies was the age groups of the participants, which might have influenced the outcomes. Therefore, their findings instill us to further question whether wearing compression garments (e.g., socks and bandages) bring any beneficial or deteriorating effects on postural regulation performance in older adults. With the two limited studies in the current literature, more research is needed to investigate the effects of wearable garments on in elderly populations.

6.1.2 Textured materials

In this review, we found that 8 studies did not mask (Blinding) the intervention approach to participants and researchers. In our opinion, the blinding process could be challenging as the textured material provide additional tactile sensation compared to smooth materials. Nevertheless, we suggest to apply the blinding to the researchers would deem feasible.

The qualitative synthesis showed that double-limb standing balance measurements were most commonly used in studies of textured materials. Previous studies have revealed beneficial effects of using TMSS seen in DLS task performance in young adults, middle-aged older adults (Aruin & Kanekar 2013; Corbin et al., 2007; Maki et al., 1999; Palluel et al., 2008; Palluel et al., 2009). In contrast, none of the TMSS studies investigate the effects of textured materials on participants with lower-limb injuries. The textured materials that used in the TMSS studies focused on using textual insoles to stimulate the plantar cutaneous afference from the soles of the feet. The application of textured insoles in this group of people might be less sensible as the sites that require stimulation are at the ankle or knee joints. Therefore, researcher shall apply the texture effect at the desire locations for people with lower-limb injuries. This could potentially benefit them from using textured materials in improving balance.

This review reflects the role of textured insoles in enhancing the sensorimotor signals to provide plantar cutaneous afferent information in older adults during balance and postural regulation (Hatton et al., 2011; Hatton et al., 2012; Maki et al., 1999; Palluel et al., 2008; Palluel et al., 2009; Perry et al., 2008; Qiu et al., 2012). Quantitative synthesis revealed 4 studies reported high positive effect sizes in favour of wearing added textured materials (Menz et al., 2006; Peterka, 2002; Qiu et al., 2012; Qiu et al., 2013). Menz et al. (2006) is the only study that used Velcro to stimulate the mechanoreceptors and skin receptors either at the ankle, calf, or knee. Besides the cutaneous receptors from the soles of the feet, the question of whether other sensory receptors in the lower limbs could also be stimulated by using TMSS to enhance postural regulation system function. In addition, with the localized stimulation via Velcro, could potentially help ageing individuals and people with lower-limb injuries exploit the available "sensorimotor system noise", and subsequently improving the postural regulation performance.

Overall effect size showed that textured insoles enhanced postural regulation performance in challenging conditions – during upright balance with eyes closed on a stable surface (SMD = 0.61), and in older adults (SMD = 0.30). These findings support the sensory re-weighting concept, where mechanical stimulations such as textured insoles could activate the plantar cutaneous receptors to compensate for the loss of visual information (Preszner-Domjan et al., 2012). For future studies, researchers could investigate the effects of TMSS, especially with regards to individuals with visual impairments and elderly people with eye problems (e.g., Cataract or Glaucoma etc.). It is also plausible that textured materials (e.g., insole and Velcro) could be potentially used as a medium to ameliorate adverse effects on the postural control system due to aging. In sports, we suggest athletes (e.g., in gymnastics, skiing, football etc.) to use textured materials to enhance the somatosensory feedback and reduce the dependence on visual information during the competitive performance.

6.1.3 Stochastic resonance

The qualitative synthesis showed that both SLS and DLS were most commonly used in studies using the application of stochastic resonance. Most of the included studies focused on investigating the effects of using SRSS in young and lower limbs' injured participants. The imperceptible electrical stimulation (white noise, 0.01–0.05 mA) was used to enhance balance control, by reducing postural sway during performance in static balance tasks (Amiridis et al., 2005; Dickstein et al., 2005; Gravelle et al., 2002; Magalhães & Kohn, 2012; Magalhães & Kohn, 2014; Ross et al., 2007; Ross, 2007; Ross et al., 2013).

Quantitative synthesis showed moderate- to high-pooled effect sizes in most of the populations and categories studied in young (SMD = 0.66) and older adults (SMD = 0.31), and static balance tasks (SMD = 0.49–0.55). This finding supports that direct application of weak input signals (non-zero level of noise) enhanced the detection of sensorimotor signals, which were beneficial to motor task performance (e.g., balance) (Cordo et al., 1996; Martínez et al., 2007). During the DLS task performance in an eyes-closed condition, the moderate effect size (SMD = 0.58) of Kimura and Kouzake (2013) study prompts speculation that SRSS might also be effective under a condition where reliance on somatosensory system information (Kimura & Kouzaki, 2013). This suggests the possibility of using Stochastic Resonance to enhance somatosensory system signals and reduce the reliance on visual information for basic postural control.

The common sites of the electrical stimulation in all included studies were along the shank, and between the ankle and knee joints. Most of the electrodes were placed on the muscles, ligaments, and bone (lateral and medial side of femoral condyles) to stimulate the respective receptors. Therefore, it is plausible that muscle spindles and mechanoreceptors along the shank were sensitive to the stimulation by SR. It was found that older adults, patients with lower limb injuries, as well as healthy young adults benefitted from the stimulation applied at these sites (e.g., shank, and between the ankle and knee joints).

Interestingly, none of the previous studies measured the effects of SRSS on athletic performance and using athletes as the study sample. The reasons for not adopting the SRSS in sports context could be due to the practicality issue as it is an inconvenience to wear the wired electrical stimulation during sports performance. Nevertheless, with the advancement of technology, researcher could consider wireless transmission of electrical stimulation placed within a tight suit (e.g., alpine skier). Computer modeling could be another viable method to study the effect of imperceptible electrical stimulation (white noise, 0.01–0.05 mA) on postural regulation performance in athletes.

6.2 Falls, cognition and balance (Study II)

In comparison with the study done by Chan et al. (1997), the current finding showed that the prevalence of falls has increased from 17.2% to 27.8% in these two decades. The percentage of falls were similar to the findings found in other countries such as United State, United Kingdom, Hong Kong, and Korea were 28.7% (Bergen et al., 2016), 28.4% (Gale et al., 2016), 16.5% (Björk et al., 2019), and 33.1% (Lee et al., 2018). Our study also showed that community-dwelling elderly individuals who were most at risk of falling having mild cognitive impairment and balance impairment. Our study's outcome also support that age has inversed relationship with cognitive functions (Fischer et al., 2014; Härlein et al., 2011; Mirelman et al., 2012; Muir et al., 2012; Taylor et al., 2013) and balance abilities (Jeon & Kim, 2017; Thorbahn & Newton, 1996) as observed in the previous studies. In agreement with previous studies done by Muir et al. (2012) and Tangen et al. (2014), cognition and balance control has a direct positive relationship. We observed that a decline in cognition resulted a lower score in Berg Balance test. Furthermore, we found that both cognitive and balance scores are the risk factors to falls. This observation supports the possible mechanism of the ageing of the frontal cortex which primarily focuses on cognitive, attention and executive function (e.g., slow response inhibitions and judgment errors) (Gunning-Dixon & Raz, 2000; Mirelman et al., 2012; Rose, 2010). Therefore, the decline in cognitive function observed might explain the increased risk of falling in this sampled population.

We observed a subtle decline in cognition (mild cognitive impairment) in Singapore's community-dwelling elderly individuals. The MMSE scores were below the average as compared to other studies conducted in the United State, Japan, Korea, Brazil, China, United Kingdom, and Turkey (Arguvanli et al., 2015). Härlein et al. (2011) suggested that education is one of the primary protective mechanisms for cognitive impairment. Our study showed that the majority of this sampled group (79.5%) had received less than 6 years of education, which could be the lead factor to mild cognitive impairment. It was reported that cognitive impairment was less likely to appear in a group of highly educated elderly individuals, aged 70–79 years old (Seeman et al., 2005). Albert (1995) explained that the effects of education on cognitive ability link to the number of synaptic density in the brain. He suggested that the increment of synaptic density in the brain in the early stages of life could delay the appearance of cognitive declines in old age (Albert, 1995). Nevertheless, a cognitive function could be improved by an intervention exercise that combined cognitive and motor training (e.g., interactive cognitive-motor video game dancing) (Eggenberger et al., 2016).

The mean BBS scores of this study showed that community-dwelling elderly people living in Singapore were within the low fall risk category (41 – 56 scores). This sampled group scored higher than the study conducted in Korea (Jeon & Kim, 2017) but it was below the average as compared to the elderly people living in Canada (Muir et al., 2010; Stevenson et al., 2010). In agreement to Jeon and Kim (2017), our study found that a cut-off point of 40 seemed to have a predictive value for risk of falls instead of the cut-off point of 45, suggested by Berg et al. (1992). Correlation analysis showed a moderate relationship between MMSE and BBS test scores in young- and medium-old age groups. Therefore, a decline in cognitive ability might have led to a decrease in balance performance, which might increase the fall risk.

6.3 Effects of knee length socks of various compression levels

The findings of study III suggest that wearing compression knee length socks benefit the community-dwelling elderly men and women in postural regulation. In elderly men, beneficial effects were observed in the AP direction in both SO and FO task conditions. Similarly, wearing NCC KLS reduced the sway area, trace length, and sway velocity while standing on the foam surface with eyes open in elderly women. Nevertheless, compression KLS did not improve the postural regulation of both elderly men and women when they were performing the standing balance task during a challenging condition - unstable surface and without vision (FC).

In study IV, the results showed that wearing both CC and NCC KLS decrease mean absolute errors in the ankle joint awareness test. Second, a significant interaction between treatments and levels of surface slopes was observed for absolute errors measurement in the elderly men. Specifically, wearing KLS improved the accuracy of ankle joint position estimation, especially for the surface slopes number 4 (10°) and 5 (12.5°). However, this study showed that the beneficial effects of wearing KLS were not prominent in the elderly women.

6.3.1 Double-leg standing balance (Study III)

The present research adds to the literature supporting the use of compression socks in older adults, as evidenced by significantly improved postural regulation in FO task condition. The results of this study support idea that lower-limb sensory stimulation strategy through wearable garments decreased postural sway during static balance task (Birmingham et al., 2001; Genthon et al., 2010; Hadadi et al., 2011; Kuster et al., 1999). Kuster et al. (1999) found that ACL reconstruction patients benefit from wearing compression sleeves by decreasing the postural sway in the AP direction where the similar observation was found in the elderly men of this study. In contrast to Hijmans et al. (2009), our study showed that compression socks enhance the postural regulation in elderly people. It was noted that the participants' age range of Hijmans et al.'s (2009) study was between 75 and 95, whereas our participants' age group was between 65 and 84 years old. With the randomized controlled trial approach used in the present study, we suggest that clinical and non-clinical levels compression socks benefit the older adults in regulating their balance especially on unstable surface. In addition, our findings might imply that wearable compression garments only benefit elderly people up to a specific age range.

We propose that compression KLS seems to have a similar beneficial effect in enhancing the postural regulation system's function as wearing textured insoles (Genthon et al., 2010; Kunzler et al., 2013; Orth et al., 2013; Qiu et al., 2012; Woo et al., 2017b). Based on the essential noise concept by Davids et al. (2003), it is possible that the compression effects of KLS exploit the availability of sensorimotor system noise to enhance the perception of proprioceptive and haptic information during the performance of complex tasks (e.g., standing on an unstable surface). We suggest that the knee-length compression socks provide constant stimulation and interact with the biological cueing system through cutaneous receptors to enhance the somatosensory system as discussed in Kraemer's study (Kraemer et al., 1998). From the neuromotor function perspective, it seems that wearing compression KLS yielded similar effects of using electrical stimulation, whereby it increases motor neuron excitability of H-reflex and down-modulated the Hoffmann Reflex (H-reflex) (Mynark & Koceja, 2002; Nishikawa & Grabiner, 1999; Taube et al., 2008). The similarity between compression KLS and electrical stimulation is both stimulate various cutaneous mechanoreceptors, motor neurons, and muscle proprioceptors along the shanks. This suggests that the alteration of afferent information via compression KLS is sufficient to overcome the inherent difficulties of the challenging task, such as standing on an unstable surface (e.g., foam surface).

Pelliccioni et al. (2014) found that the amplitude and conduction velocity of motor and sensory nerves significantly differ with gender (Pelliccioni et al., 2014). These factors could be potentially attributed to the gender-based differences observed from wearing the compression KLS in our study. Consistent with the findings of Olchowik et al. (2015), men displayed less postural sway than women in the AP direction (Olchowik et al., 2015). This suggested that men might employ a better movement strategy and orientation in anterior-posterior directions during the upright standing task. Our study showed that wearing clinical compression KLS further enhance the AP movement strategy in elderly men, as supported by the decrease in the sway distance in the AP direction. Similarly, positive performance outcomes in many COP variables such as sway area, trace length, and sway velocity were observed in elderly women while wearing clinical compression KLS. It was suggested that women are more effective in using the ankle strategy to regulate balance than men (Olchowik et al., 2015; Pelliccioni et al., 2014). Our findings suggest that wearing compression KLS seems to be able to stimulate the receptors around the ankle joint and aid the ankle control strategy.

During upright balance on a foam (unstable) surface with eyes open (i.e., availability of vision) task, wearing KLS enhanced postural regulation performance in a challenging condition. This phenomenon was also observed in Qiu et al.'s (2012) study by using textured insoles as lower-limb sensory stimulation strategy. The role of somatosensory feedback is assumed to be more critical when standing on an unstable surface (Patel et al., 2008; Vuillerme & Pinsault, 2007). When the somatosensory is compromised, our study showed that wearing compression KLS seemed to enhance afferent sensory information to the Central Nervous System (CNS) and facilitated the perceptual regulation of stance. In contrast to Qiu et al. (2017), no immediate beneficial effects was found of wearing compression KLS when both vision and somatosensory are compromised. This finding could imply that the somatosensory system stimulation provided by wearing compression KLS is not sufficient to yield beneficial effects when sensory perturbations seemed to be too severe (e.g., standing on a foam surface with eyes closed). However, more studies are needed to confirm the beneficial effects of wearing compression KLS on postural regulation in the FC condition.

6.3.2 Joint position sense (Study IV)

Our study found that wearable garment such as compression socks has the similar positive effects on joint positioning, as observed in studies using ankle braces and tapes (Iris et al., 2010; Larsen et al., 2015; Long et al., 2016; Nishikawa & Grabiner, 1999). We found that wearing clinical compression and non-compression socks reduced the absolute errors during the estimation of ankle joint (plantar flexion) test. Our findings were in agreement with Hijmans et al. (2009), where the use of clinical compression socks reduced the perception errors at the ankle joint. Furthermore, consistent with the findings by Barss et al. (2018), wearing compression materials could improve the joint's sensitivity and precision. A recent study done by Ghai et al. (2018) found that wearing below-knee compression garments improved joint proprioception by reducing the mean errors of a repositioning task (Ghai et al., 2016). Two studies mentioned that compression garments (e.g., sleeves) could alter the excitability of cutaneous reflexes (Barss et al., 2018) and increase motor neuron excitation in the afferent system (Nishikawa & Grabiner, 1999). These attributes of compression garments might be the factors of the improvement observed on the joint's precision task in this study. Therefore, the current study suggests that wearable garments with compression function might exploit the availability of "sensorimotor system noise" to enhance the perception of proprioception to better estimate the joint position, especially at the distal end (ankle) of the lower limbs, in elderly people.

A significant interaction between treatments and surface slopes of joint position sense in the elderly men was observed in this present study. It showed that wearing compression and non-compression KLS significantly reduced the absolute errors for the mid-range ankle positions, sloped surfaces 4° (10°) and 5° (12.5°). It was suggested that the larger JPS errors occurred at the mid-range (e.g., 12.5°) of plantar flexion movement. It is because it is more difficult to estimate the perceived angle due to the firing of muscle receptors and activation of cutaneous receptors functions in the mid-range (e.g., 12.5°) of plantar flexion (Iris et al., 2010; Sekizawa et al., 2001). In addition, Robbins et al. (1995) suggested that significant changes in proprioception ability for the movements over 10° either in plantar-or dorsiflexion (Robbins et al., 1995). The positive findings of the present study suggest the possibility of wearing KLS could enhance the firing of the muscle receptors and activation of cutaneous receptors during the mid-range angles of plantar flexion. On the other hand, as the surface slope greater than 10° in plantar flexion presumed to be the most crucial range to an ankle injury (Robbins et al., 1995), wearing KLS could potentially be used by athletes to reduce the ankle injury.

The effect of wearing KLS on the direction of imprecision for the joint position sense task was unclear. Our finding showed a trend of reduction of constant errors by wearing KLS. The analysis based on gender did not show any significant beneficial effects of wearing KLS in the elderly women. This could attribute to the gender-based differences as the amplitude, and conduction velocity of motor and sensory nerves are found different between genders (Pellicioni et al., 2014). Another factor could be the muscular strength differences in elderly men and women as muscular force is inversely proportionate to the joint position sense errors (Westlake & Culham, 2006). On the other hand, our study found that both elderly men and women had the trend towards underestimation of the required position. The underestimation of surface slope could be an indication of the inadequacy of muscle contraction in providing information to support the feet for a required foot position (Robbins et al., 1995). We suggest that wearing KLS could possibly enhance the command of muscle contraction, thereby reduced the constant errors as seen in the elderly men.

6.4 Methodological considerations

This dissertation utilized multiple research designs to gather in-depth information about lower-limb sensory stimulation strategies and to minimize the risk of biases in the selection of participants. In study I, a systematic review and meta-analysis was carried out to review the current literature review and its effectiveness on postural regulation. This approach allows the researcher to conduct the review systematically and to sum up research findings in a more differentiated and sophisticated manner. It focuses on the direction and magnitude of the effects across studies and allow researcher to have an in-depth interpretation of the included studies. For the grouping of WGSS, TMSS, and SRSS, we considered the characteristic of lower-limb sensory stimulation strategies. For example, wearable garments group included fabric materials, braces, and tapes that are used to wrap/paste around the joints and muscles of the lower limbs. Textured materials group included the textured insoles and Velcro that were used for rubbing against the skin. Stochastic Resonance group involved the studies used imperceptible electrical stimulation (white noise). For the meta-analysis component, some studies were not included because of the different measurement units used in their respective studies. This could have an impact on the final effect sizes of the meta-analysis outcome.

In study II, a total of 385 community-dwelling elderly people were recruited from various senior activity centers in Singapore. The invitation emails were sent to various centers of different zones (North, South, East, West, Central). The majority of the responded centers were located in the South zone of Singapore. This might be due to the distribution of government housing for elderly people are mostly located in that area. Therefore, the sample of this study may be better reflected and represented the elderly people who are living in the South zone of Singapore. The distribution of the ethnicity percentage was found closely resembled the national ethnicity distribution in Singapore. As the elderly participants were from Singapore, we then adopted the age groups' definitions by Singapore's Department of Statistic. The age groups of the elderly people were identified as "young-old (65–74 years)", "medium-old (75–84 years)", and "oldest old (above 85 years)" in this dissertation. The primary aim of this cross-sectional study was to collect demographic data, medical history, fall history, balance ability, and cognitive levels. This information collected was then used for participants' selection in studies III and IV. In studies III and IV, the main aim was to investigate the effects of KLS of various compression levels on somatosensory function. Therefore, the participants that were randomly selected and recruited for studies III and IV need to meet the inclusion criteria with normal cognitive function and low risk of falls. This was to minimize the numbers of confounding factors when we investigate the effects of KLS.

Measurement methods used in study II involved Health Activity Questionnaire, Berg Balance Scale, and Mini-mental State Examination. These measurement methods were chosen because of its suitability, good reliability and validity for the elderly population (Rose, 2012). The other reason for choosing the tests was because of the minimal logistic requirement in conducting the tests. Therefore, it makes it more convenient for the researcher to collect data at the respective senior activity centers. In study III, the balance task included the vision (eyes open and eyes closed) and surface (foam and stable) conditions. With the absence of visual component and on foam surface during double-leg static balance task, it put greater reliance on the somatosensory system. The manipulation of vision and surface conditions would provide a better understanding of the effects of KLS on somatosensory sensory. In study IV, foot position awareness was being measured by using a modified slope box with multiple adjustable angles. The primary purpose of study IV was to investigate the effects of KLS on perception regulation of action. Joint position sense (JPS) test is an assessment of proprioception (Suetteline & Sayer, 2014) and it determines the participant's ability to comprehend a presented joint angle (Ribeiro & Oliveira, 2007). One of the recommended assessments is via surface slope test where participants are asked to indicate the steepness of a slope box (Hijmans et al., 2007; Robbins & Waked, 1997). It was suggested that testing joint proprioception in a weight-bearing position (e.g., standing position) is more relevant to the identification of fall risk (Suetterlin & Sayer, 2014). Therefore, the joint position sense on the slope box was in a standing position. We chose of plantar flexion movement as the main testing action because it was found that estimate angle error was the greatest in this direction (Sekizawa et al., 2001). This would help us better identify the effects of KLS on perception regulation of action.

Postural sway is the lowest for the normal, healthy participants in the eyes-opened condition; and the greatest when the visual and somatosensory information are absent or altered (see Riley & Clark, 2003). For the data reporting, stabilometric data such as postural sway (C90) area, trace length, AP postural sway and AP SD, ML postural sway and ML SD, and COP sway velocity were used in study III. Furthermore, variables such as the mean speed and the mean amplitude of the medial-lateral movement of CoP were reported as the indicators that showed significant associations with future falls (Melzer et al., 2010; Moghadam et al., 2011; Piirtola & Era, 2006). Seigle et al. (2009) proposed that sway area, the length of the CoP displacement, sway velocity are the most reliable CoP stabilometric parameters in measuring postural stability. They also suggested that the length of the CoP displacement was the best discriminating parameter for both visual and aging effects. Therefore, the above CoP related parameters were included in the results reporting section. For study IV, we deemed that wearing KLS was effective when the estimate errors from the target angle were reduced. There were two main types of errors, absolute and constant errors, were reported in this study. Absolute errors measures indicated the precision of estimates (Robbins & Waked, 1997). The constant error refers to the direction of position errors from the target position, positive value for overestimation, and negative for underestimation.

A strength of the present study was the use of randomisation approach in multiple areas such as participants selection, sequence order of intervention treatments (e.g., CC KLS, NCC KLS, NC KLS, Bare), sequence order of task conditions (e.g., SO, SC, FO, FC) in balance testing, and sequence order of ankle joint movements (e.g., 2.5°, 5.0°, 7.5°, 10.0°, 12.5°, 15.0°, 17.5°, 20.0°). This reduces the researcher's biases in selecting a particular group of participants. The randomization of the sequence orders of intervention treatments and task conditions prevent carry-over effects for participants. Therefore, the outcome of the data was unpredictable, and this minimizes the risk of bias for research.

It is strength of the present study that we explore novel intervention treatments, KLS with various compression levels, on somatosensory function in the elderly people. Clinical level compression socks have been used to treat deep vein thrombosis and edema in a medical setting (Blättler & Zimmet, 2008). Furthermore, most of the research on socks focused only on a few areas - prevention of foot lesion such as blisters, ulcers, calluses and sores (Dai et al., 2006); biomechanical response in walking and running (Tsai & Lin, 2013); slip and fall (Hübscher et al., 2011; Koepsell et al., 2004). The proposed treatment interventions build on recently published work examining the effect of textured footwear on the functions of the peripheral and central nervous systems (Corbin et al., 2007; Hijmans et al., 2007; Perry et al., 2008). Studies reported that the use of textured insoles enhances postural regulation in elderly people. Therefore, we were intrigued by the idea of whether compression function could enhance postural regulation by contortion and disturbances of haptic system receptors in the skin and soft tissue of the lower limbs.

6.5 Limitations

In study I, the limitations for the systematic review and meta-analysis paper were, i) some data was extracted from graphs when values were not reported, ii) solely focused on studies underwent vigorously, external peer review in international, scientific journals, and iii) varied in intervention duration of the lower-limb sensory stimulation strategies. These limitations might have had some impacts on the overall effects size calculation for the quantitative synthesis. In study II, the

Fallproof Health and Activity questionnaire was conducted through an interview where participants self-report about their medical conditions, fall history, and daily physical activity. Therefore, there was a possibility of under-reporting by the older participants. For example, older participants might under-report the number of falls where they don't want to be seem as frail older adults. Therefore, the total number of falls reported directly impacted the outcomes of this study, particularly the risk factors of falls and its' relationship to cognitive and balance abilities. As the interview process was conducted in local languages and dialects, there might have a chance that the elderly did not understand thoroughly about the questions asked which might have impacted the way they answered. For the MMSE test to examine the cognitive levels, the limited education of this group of participants might have affected the scores.

In study III, we did not conduct any assessment of the lower-limb muscle strength capacity. Therefore, it is unknown whether individual variations in muscle strength affected the performance outcomes. In study IV, the levels of the working memory and attentional load in this group of elderly might predispose older adults to poor performance on this memory-based joint position matching tasks. Researchers could consider reducing the number of stages of the slopes, and replacing the assigned corresponding number with visual representation images. Another limitation could be the use of a modified slope box with passive JPS test instead of a Biodex System Isokinetic Dynamometer with an active JPS test. The modified slope box was chosen due to low education levels and lack of understanding of the concept of angles in this group of participants.

In both studies III and IV, some participants shared that it was uncomfortable to wear the clinical level compression KLS (20–30 mmHg). This could have affected their performance during the double-limb standing balance and joint position sense tasks. Besides, the lack of previous studies in the areas of using compression socks on somatosensory function in the elderly population could have impacted the depth of the discussions on the effects of compression KLS on postural regulation. It is to note that the scope of this program focus on the acute effects of compression KLS in older adults. Nevertheless, we noted that our results couldn't be fully generalized on clinical populations with known balance impairments and sensory deficits.

6.6 Implications and future research

From the systematic review and meta-analysis study, we found that lower-limb sensory stimulation strategies used in the previous studies aid to the somatosensory system in postural regulation tasks. The significant implication of this review is that health professional, the general public, and athletes could adopt these stimulation strategies to attune information from the lower limbs for improving their balance abilities. In this review, we found that an application of Stochastic Resonance has produced the most effective results but it is more costly and less convenient to implement, compares to using textured materials and wearable garments. We noticed that WGSS benefitted patients with lower-limb injuries and limited studies (n = 2) were found in the elderly population. Therefore, more research shall be conducted to investigate the effects of WGSS, especially compression garments on the somatosensory system function in elderly people. Future research shall also study the effects of integrating two low-cost lower-limb stimulation strategies such as wearing textured and compression materials on the somatosensory system function in sports and clinical settings, particularly for developing athletes, and people with sensory function disorders or due to degeneration. For task performance difficulty levels, we suggest to include the use of unstable surface and in an eyes-closed condition and walking on uneven to better differentiate the effectiveness of lower-limb sensory stimulation strategies. Future research could consider including an eyes-closed condition to measure the effects of applying TMSS and WGSS on somatosensory system function and its effects on visually impaired populations.

The implication of our studies (Study III & IV), wearing compression KLS seemed to stimulate the various cutaneous mechanoreceptors, motor neurons, and muscle proprioceptors along the shanks. Therefore, compression KLS could potentially form a strategy to ameliorate negative effects of ageing on the postural control and proprioception systems, improve perceptual-motor system and reduce risk of falling. Therefore, compression KLS could be a potential intervention to be adopted by health professionals and the general public to enhance their somatosensory system. In study III, we noticed that wearing KLS seems to aid the ankle control strategy. This highlights a research area to compression garments manufacturers where the sock designs could be enhanced, by concentrating the stimulation materials (e.g., compression levels and textured undulations) surrounding the ankle and at the anterior-posterior aspect of the compression KLS. Furthermore, we found that KLS enhanced the performance in a challenging condition – during upright balance on a foam surface with eyes open. Future research could consider investigating the effects of KLS on the population with decreased function in the somatosensory system. In study IV, wearing knee length socks could have boosted detection of sensorimotor signals, amplifying the muscle and cutaneous receptors in the lower limbs and thereby improve the proprioception. It was noted that proprioception was improved by the use of both compression and non-compression knee length socks for the plantar flexion position, especially for the surface slopes at 10° and 12° in the elderly men. Future studies could investigate the relationship between wearable garments, the ankle joint positioning, and the firing of muscle and cutaneous receptors in the lower limbs. In future work, it would be of interest to examine the effects of KLS for a more extended period. For examples, the relationship between the overall comfort of wearing the knee length socks, postural regulation, and JPS performance, especially the effects of wearing KLS on the direction of imprecision in the elderly population.

The major implication of the cross-sectional study (Study II) is that health professionals to predict the falls in elderly individuals, aged below 85 years old, could use MMSE and BBS tests. We found a moderate relationship between cognitive decline and the risk of falls. Therefore, either test could be used as a simple screening tool to incorporate in a routine primary care assessment for Singapore population. Future research could consider collecting longitudinal data in the area of cognitive function and balance ability in this group of elderly to better monitor the rate of deterioration. This could help health professionals to apply appropriate interventions for fall preventions.

7 MAIN FINDINGS AND CONCLUSION

The main findings of this study are:

Wearable garments as an intervention were effective in studies of patients with lower-limb injuries, and textured materials lower-limb stimulation strategy was found to be beneficial in young and healthy population in a double-leg standing task.

An application of Stochastic Resonance has produced the most effective results in postural regulation, compared to implementing interventions with wearable garments and textured materials.

Balance ability and cognitive functioning levels were the most significant risk factors for falls. A moderate relationship was found between MMSE and BBS test in the young-old (65–74 years old) and medium-old (75–84 years old) groups.

Wearing compression socks enhanced postural regulation by reducing the postural sway while standing on a foam surface in the elderly population.

Wearing compression socks decreased anterior-posterior sway in elderly men while wearing compression socks decreased sway area and sway velocity in elderly women.

Wearing both clinical compression and non-compression knee length socks significantly reduced overall joint position sense errors. The significant decreased in absolute errors were observed for the surface slopes number 4° (10°) and 5° (12.5°) in men.

SUMMARY

Research has demonstrated that lack of ability in balance control is associated with a higher risk of falling. During an upright stance, the body is never perfectly still. The body continually exhibits irregular, low-amplitude motion, continuous displacements around the actual vertical upright stance, termed postural sway. The somatosensory system has the greatest influence in the detection of body sway and provides the greatest information to healthy individuals to regulate the centre of pressure in a stable and well-lit environment. Studies have shown that feedback from the cutaneous afferents is an essential mechanism in regulating the CoP, especially the pressure changes under the feet. The functional role of variability induced in the sensorimotor system by wearable garments acts as a form of "essential noise," which helps individuals regulate actions. Therefore, it may help performers to pick up information from the background signals to enhance the perception of somatosensory feedback.

The research programme consists of three study designs – systematic review and meta-analysis, cross-sectional, and repeated measures (experimental). For the systematic review and meta-analysis, a total of 49 studies were included for qualitative synthesis. 28 out of 49 studies were included for quantitative synthesis. For the cross-sectional study, 385 community-dwelling elderly individuals aged 65 years old and above, randomly recruited from Singapore communities such as senior activity centres. For the repeated measures study in studies III (N = 46) and IV (N = 48), participants who met the inclusion criteria were randomly selected from the participants' pool in the cross-sectional study. Ethics approval was sought from the ethical committee of the University of Jyväskylä and Nanyang Technological University, Singapore for this research programme. Fallproof Health and Activity Questionnaire was used to collect the background information such as medical conditions, falls frequency, description of falls, and physical activities. Mini-Mental State Examination (MMSE) questionnaire was used to categorise the cognitive levels. Berg Balance Scale test was used to identify balance ability. Double-limb standing balance (30-s Romberg test) task under two vision conditions (eyes open and closed) on two standing surfaces (stable and foam) was used to measure the postural sway and regulation. A modified slope box text protocol was used to measure joint position awareness. For the experimental study (Studies III & IV), a repeated-measure design was used to determine effects on postural regulation and joint position awareness of three different intervention treatments – wearing clinical compression socks; wearing non-clinical compression socks; wearing commercial socks, and barefoot (Control).

In comparison to wearable garments and textured materials interventions, our review of published studies indicates that an SRSS has produced the most effective results in postural regulation. Our review showed that young adults and elderly people benefit from wearing texture materials (e.g., insoles). It showed that WGSS was effective for patients with lower-limb injuries. For the

community-dwelling, elderly individuals in Singapore, findings revealed balance ability and cognitive functioning levels were the biggest risk factors for falls. Participants above 85 years of age had the highest number of fall incidents, combined with mild cognitive impairments and low Berg balance scale scores. Our study showed that wearing compression knee length socks enhanced postural regulation by reducing the postural sway, especially standing on a foam surface in the elderly population. Furthermore, our study showed that wearing compression and non-compression knee length socks improved the precision of estimation of ankle joint plantar flexion movement, by reducing the absolute errors in the elderly people. Therefore, wearing compression knee length socks could potentially be used as one of the interventions to reduce the risk of falling. This could potentially form an affordable strategy to ameliorate the negative effects of ageing on the perceptual-motor systems. In addition, it could be potentially be part of the rehabilitation programme to aid people with proprioceptive deficit due to injuries. Further research evaluating the long-term effects of compression KLS is necessary.

REFERENCES

Aimonetti, J. M., Hospod, V., Roll, J. & Ribot-Ciscar, E. 2007. Cutaneous afferents provide a neuronal population vector that encodes the orientation of human ankle movements. *The Journal of Physiology* 580 (2), 649-658.

Al Saif, A., Waly, E. & Alsenany, S. 2012. The prediction of falls among older people in Saudi Arabia. *Journal of American Science* 8 (6), 696-700.

Alan, L. 2011. Neuroscience. 3rd edition. New York: Taylor & Francis.

Albert, M. S. 1995. How does education affect cognitive function? *Annals of Epidemiology* 5 (1), 76-78.

Amiridis, I. G., Arabatzi, F., Violaris, P., Stavropoulos, E. & Hatzitaki, V. 2005. Static balance improvement in elderly after dorsiflexors electrostimulation training. *European Journal of Applied Physiology* 94 (4), 424-433.

Anstey, K. J., Von Sanden, C. & Luszcz, M. A. 2006. An 8-Year prospective study of the relationship between cognitive performance and falling in very old adults. *Journal of the American Geriatrics Society* 54 (8), 1169-1176.

Anstey, K. J., Wood, J., Kerr, G., Caldwell, H. & Lord, S. R. 2009. Different cognitive profiles for single compared with recurrent fallers without Dementia. *Neuropsychology* 23 (4), 500-508.

Arguvanli, S., Akin, S., Deniz Safak, E., Mucuk, S., Öztürk, A., Mazicioğlu, M. M., Kizilçay, H. D. & Göçer, S. 2015. Prevalence of cognitive impairment and related risk factors in community-dwelling elderly in Kayseri, Turkey. *Turkish Journal of Medical Sciences* 45 (5), 1167-1172.

Aruin, A. S. & Kanekar, N. 2013. Effect of a textured insole on balance and gait symmetry. *Experimental Brain Research*. 231 (2), 201-208.

Baier, M. & Hopf, T. 1998. Ankle orthoses effect on single-limb standing balance in athletes with functional ankle instability. *Archives of Physical Medicine and Rehabilitation* 79 (8), 939-944.

Barss, T. S., Pearcey, G. E., Munro, B., Bishop, J. L. & Zehr, E. P. 2018. Effects of a compression garment on sensory feedback transmission in the human upper limb. *Journal of Neurophysiology* 120 (1), 186-195.

Bassiony, M. M. 2004. Falls and age in patients with Alzheimer's Disease. *Journal of Nervous and Mental Disease*. 192 (8), 570-572.

Berg, K. O., Maki, B. E., Williams, J. I., Holliday, P. J. & Wood-Dauphinee, S. L. 1992a. Clinical and laboratory measures of postural balance in an elderly population. *Archives of Physical Medicine and Rehabilitation* 73 (11), 1073-1080.

Berg, K. O., Wood-Dauphinee, S. L., Williams, J. L. & Maki, B. 1992b. Measuring balance in the elderly: Validation of an instrument. *Canadian Journal of Public Health* 83 (Suppl 2), 7.

Bergen, G., Stevens, M. R. & Burns, E. R. 2016. Falls and fall injuries among adults aged ≥ 65 years — United States, 2014. *Morbidity and Mortality Weekly Report* 65 (37), 993-998.

Birmingham, T. B., Kramer, J. F., Kirkley, A., Inglis, J. T., Spaulding, S. J. & Vandervoort, A. A. 2001. Knee bracing after ACL reconstruction: Effects on postural control and proprioception. *Medicine and Science in Sports and Exercise* 33 (8), 1253-1258.

Björk, A., Ribom, E., Johansson, G., Scragg, R., Mellström, D., Grundberg, E., Ohlsson, C., Karlsson, M., Ljunggren, Ö & Kindmark, A. 2019. Variations in the vitamin D receptor gene are not associated with measures of muscle strength, physical performance, or falls in elderly men. Data from MrOS Sweden. *Journal of Steroid Biochemistry and Molecular Biology* 187, 160-165.

Błaszczyk, J. W. & Michalski, A. 2006. Ageing and postural stability. Poznań: Akademia Wychowania Fizycznego w Poznaniu.

Blättler, W. & Zimmet, S. 2008. Compression therapy in venous disease. *Phlebology* 23 (5), 203-205.

Borenstein, M., Hedges, L., Higgins, J. & Rothstein, H. 2009. Introduction to meta-analysis. United Kingdom: John Wiley & Sons, Ltd.

Bradley. S. M. 2011. Falls in older adults. *Mount Sinai Journal of Medicine* 78 (4), 590-5.

Broglio, S. P., Monk, A., Sopiarz, K. & Cooper, E. R. 2009. The influence of ankle support on postural control. *Journal of Science and Medicine in Sport* 12 (3), 388-392.

Bryant, E. C., Trew, M. E., Bruce, A. M., Kuisma, R. M. E. & Smith, A. W. 2005. Gender differences in balance performance at the time of retirement. *Clinical Biomechanics* 20 (3), 330-335.

Cavanaugh, M., Quigley, P., Hodgson, D., Reid, J. & Behm, D. 2016. Kinesiology tape or compression sleeve applied to the thigh does not improve balance or muscle activation before or following fatigue. *Journal of Strength and Conditioning Research* 30 (7), 1992-2000.

Chan, K. M., Pang, W. S., Ee, C. H., Ding, Y. Y. & Choo, P. 1997. Epidemiology of falls among the elderly community dwellers in Singapore. *Singapore Medical Journal* 38 (10), 427-31.

Chu, L. W., Chi, I. & Chiu, A. 2005. Incidence and predictors of falls in the Chinese elderly. *Annals Academy of Medicine Singapore* 34(1), 60-72.

Collings, R., Paton, J., Chockalingam, N., Gorst, T. & Marsden, J. 2015. Effects of the site and extent of plantar cutaneous stimulation on dynamic balance and muscle activity while walking. *Foot* 25 (3), 159-163.

Collins, A. T., Blackburn, J. T., Olcott, C. W., Miles, J., Jordan, J., Dirschl, D. R. & Weinhold, P. S. 2012. Stochastic resonance electrical stimulation to improve proprioception in knee osteoarthritis. *The Knee* 18 (5), 317-322.

Corbin, D. M., Hart, J. M., McKeon, P. O., Palmieri-Smith, R., Ingersoll, C. D. & Hertel, J. 2007. The effect of textured insoles on postural control in double and single limb stance. *Journal of Sport Rehabilitation* 16 (4), 363.

Cordo, P., Ingils, J. T., Verschueren, S., Collins, J. J., Merfeld, D. M., Rosenblum, S., Buckley, S. & Moss, F. 1996. Noise in human muscle spindles. *Nature* 383 (6603), 769-770.

Dai, X. Q., Li, Y., Zhang, M. & Cheung, J. T. 2006. Effect of sock on biomechanical responses of foot during walking. *Clinical Biomechanics* 21 (3), 314-321.

Davids, K., Shuttleworth, R., Button, C., Renshaw, I. & Glazier, P. 2003. "Essential noise" - enhancing variability of informational constraints benefits movement control: A comment on Waddington and Adams. *British Journal of Sports Medicine* 38 (5), 601-605.

Dickstein, R., Laufer, Y. & Katz, M. 2005. TENS to the posterior aspect of the legs decreases postural sway during stance. *Neuroscience Letters* 393 (1), 51-55.

Doyle, R., Hsiao-Wecksler, E., Ragan, B. & Rosengren, K. 2006. Generalizability of center of pressure measures of quiet standing. *Gait & Posture* 25 (2), 166-171.

Du Pasquier, R. A., Blanc, Y., Sinnreich, M., Landis, T., Burkhard, P. & Vingerhoets, F. J. G. 2003. The effect of aging on postural stability: A cross sectional and longitudinal study. *Clinical Neurophysiology* 33 (5), 213-218.

Eggenberger, P., Wolf, M., Schumann, M. & de Bruin, E. D. 2016. Exergame and balance training modulate prefrontal brain activity during walking and enhance executive function in older adults. *Frontiers in Aging Neuroscience* 8 (66), 1-16.

Fabre, J. M., Ellis, R., Kosma, M. & Wood, R. H. 2010. Falls risk factors and a compendium of falls risk screening instruments. *Journal of Geriatric Physical Therapy* 33 (4), 184-197.

Field, A. 2009. Discovering statistic using SPSS (3rd ed.) - and sex and drugs and rock 'n' roll. London: SAGE.

Fischer, B. L., Gleason, C. E., Gangnon, R. E., Janczewski, J., Shea, T. & Mahoney, J. E. 2014. Declining cognition and falls: Role of risky performance of everyday mobility activities. *Physical Therapy* 94 (3), 355-362.

Fitzpatrick, R. & McCloskey, D. I. 1994. Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. *The Journal of Physiology* 478 (Pt 1), 173-186.

Frank, J. S. & Patla, A. E. 2003. Balance and mobility challenges in older adults implications for preserving community mobility. *American Journal of Preventive Medicine* 25 (3Sii), 157-163.

Gale, C. R., Cooper, C. & Aihie Sayer, A. 2016. Prevalence and risk factors for falls in older men and women: The English longitudinal study of ageing. *Age and Ageing* 45 (6), 789-794.

Gandevia, S. C., McCloskey, D. I. & Burke, D. 1992. Kinaesthetic signals and muscle contraction. *Trends in Neurosciences* 15 (2), 62-65.

Genthon, N., Bouvat, E., Banihachemi, J. J., Bergeau, J., Abdellaoui, A. & Rougier, P. R. 2010. Lateral ankle sprain alters postural control in bipedal stance: Part 2 sensorial and mechanical effects induced by wearing an ankle orthosis. *Scandinavian Journal of Medicine & Science in Sports*. 20 (2), 255-261.

Ghai, S., Driller, M. W. & Masters, R. S. W. 2016. The influence of below-knee compression garments on knee-joint proprioception. *Gait & Posture* 60, 258-261.

Gilman. S. 2002. Joint position sense and vibration sense: Anatomical organisation and assessment. *Journal of Neurology, Neurosurgery, and Psychiatry* 73 (5), 473-477.

Gleason, C. E., Gangnon, R. E., Fischer, B. L. & Mahoney, J. E. 2009. Increased risk for falling associated with subtle cognitive impairment: Secondary analysis of a randomized clinical trial. *Dementia and Geriatric Cognitive Disorders* 27 (6), 557-563.

Glorioso, C. & Sibille, E. 2011. Between destiny and disease: Genetics and molecular pathways of human central nervous system aging. *Progress in Neurobiology* 93 (2), 165-181.

Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A. & Swinnen, S. P. 2009. Proprioceptive sensibility in the elderly: Degeneration, functional consequences and plastic-adaptive processes. *Neuroscience and Biobehavioral Reviews* 33 (3), 271-278.

Gravelle, D. C., Laughton, C., Dhruv, N., Katdare, K., Niemi, J., Lipsitz, L. & Collins, J. 2002. Noise-enhanced balance control in older adults. *NeuroReport* 13 (15), 1853-1856.

Gribble, P. A., Taylor, B. L. & Shinohara, J. 2010. Bracing does not improve dynamic stability in chronic ankle instability subjects. *Physical Therapy in Sport* 11 (1), 3-7.

Guccione, A. A., Wong, R. A. & Avers, D. 2012. Geriatric physical therapy. (3rd ed edition) St. Louis: Elsevier/Mosby.

Gunning-Dixon, F. N. & Raz, N. 2000. The cognitive correlates of white matter abnormalities in normal aging. *Neuropsychology* 14 (2), 224-232.

Hadadi, M., Mazaheri, M., Mousavi, M. E., Maroufi, N., Bahramizadeh, M., et al. 2011. Effects of soft and semi-rigid ankle orthoses on postural sway in people with and without functional ankle instability. *Journal of Science and Medicine in Sport* 14 (5), 370-375.

Hadadi, M., Mousavi, M. E., Fardipour, S., Vameghi, R. & Mazaheri, M. 2014. Effect of soft and semirigid ankle orthoses on Star Excursion balance test performance in patients with functional ankle instability. *Journal of Science and Medicine in Sport* 17 (4), 430-433.

Halasi, T., Kynsburg, A., Tállay, A. & Berkes, I. 2005. Changes in joint position sense after surgically treated chronic lateral ankle instability. *British Journal of Sports Medicine* 39 (11), 818-824.

Härlein, J., Halfens, R. J., Dassen, T. & Lahmann, N. A. 2011. Falls in older hospital inpatients and the effect of cognitive impairment: A secondary analysis of prevalence studies. *Journal of Clinical Nursing* 20 (1-2), 175-183.

Hasan, H., Davids, K., Chow, J. Y. & Kerr, G. 2016. Compression and texture in socks enhance football kicking performance. *Human Movement Science* 48, 102-111.

Hatton, A., Dixon, J., Martin, D. & Rome, K. 2009. The effect of textured surfaces on postural stability and lower limb muscle activity. *Journal of Electromyography and Kinesiology* 19 (5), 957-964.

Hatton, A., Dixon, J., Rome, K. & Martin, D. 2011. Standing on textured surfaces: Effects on standing balance in healthy older adults. *Age and Ageing* 40 (3), 363-368.

Hatton, A., Dixon, J., Rome, K., Newton, J. & Martin, D. 2012. Altering gait by way of stimulation of the plantar surface of the foot: The immediate effect of wearing textured insoles in older fallers. *Journal of Foot and Ankle Research* 5 (1), 11.

Herrington, L., Simmonds, C. & Hatcher, J. 2005. The effect of a neoprene sleeve on knee joint position sense. *Research in Sports Medicine* 13 (1), 37-46.

Higgins, J. & Green, S. 2011. Cochrane handbook for systematic reviews of interventions. Available in: http://www.cochrane-handbook.org/.

Hijmans, J. M., Geertzen, J. H. B., Dijkstra, P. U. & Postema, K. 2007. A systematic review of the effects of shoes and other ankle or foot appliances on balance in older people and people with peripheral nervous system disorders. *Gait & Posture* 25 (2), 316-323.

Hijmans, J. M., Zijlstra, W., Geertzen, J. H. B., Hof, A. L. & Postema, K. 2009. Foot and ankle compression improves joint position sense but not bipedal stance in older people. *Gait & Posture* 29 (2), 322-325.

Hlavackova, P. & Vuillerme, N. 2012. Do somatosensory conditions from the foot and ankle affect postural responses to plantar-flexor muscles fatigue during bipedal quiet stance? *Gait & Posture* 36 (1), 16-19.

Horak, F. B. 2006. Postural orientation and equilibrium: What do we need to know about neural control of balance to prevent falls? *Age and Ageing* 35 (Suppl 2), ii7-ii 11.

Horak, F. B., Shupert, C. L. & Mirka, A. 1989. Components of postural dyscontrol in the elderly: A review. *Neurobiology of Aging* 10 (6), 727-738.

Horgan, N. F., Crehan, F., Bartlett, E., Keogan, F., O'Grady, A. M., et al. 2009. The effects of usual footwear on balance amongst elderly women attending a day hospital. *Age and Ageing* 38 (1), 62-67.

Hübscher, M., Thiel, C., Schmidt, J., Bach, M., Banzer, W., et al. 2011. Slip resistance of non-slip socks – An accelerometer-based approach. *Gait & Posture* 33 (4), 740-742.

Iris, M., Monterde, S., Salvador, M., Salvat, I., Fernández-Ballart, J., et al. 2010. Ankle taping can improve proprioception in healthy volunteers. *Foot & Ankle International* 31 (12), 1099-1106.

Jácome, C., Cruz, J., Oliveira, A. & Marques, A. 2016. Validity, reliability, and ability to identify fall status of the Berg balance scale, BESTest, mini-BESTest, and Brief-BESTest in patients with COPD. *Physical Therapy* 96 (11), 1807-1815.

Jenkins, M. E., Almeida, Q. J., Spaulding, S. J., van Oostveen, R. B., Holmes, J. D., et al. 2009. Plantar cutaneous sensory stimulation improved single-limb support time, and EMG activation patterns among individuals with Parkinson's disease. *Parkinsonism and Related Disorders* 15 (9), 697-702.

Jeon, Y. & Kim, G. 2017. Comparison of the Berg balance scale and Fullerton advanced balance scale to predict falls in community-dwelling adults. *Journal of Physical Therapy Science* 29 (2), 232-234.

Kavounoudias, A., Roll, R. & Roll, J. 1998. The plantar sole is a 'dynamometric map' for human balance control. *NeuroReport* 9 (14), 3247-3252.

Kelleher, K. J., Spence, W. D., Solomonidis, S. & Apatsidis, D. 2010. The effect of textured insoles on gait patterns of people with multiple sclerosis. *Gait & Posture* 32 (1), 67-71.

Kim, J., Kwon, Y., Eom, G., Jun, J., Lee, J., et al. 2012. Effects of vision, age and gender on structural and global posturographic features during quiet standing. *International Journal of Precision Engineering and Manufacturing* 13 (6), 969-975.

Kimura, T. & Kouzaki, M. 2013. Electrical noise to a knee joint stabilizes quiet bipedal stance. *Gait & Posture* 37 (4), 634-636.

Ko, S., Eleanor Simonsick, Nandini Deshpande & Luigi Ferrucci 2015. Sex-specific age associations of ankle proprioception test performance in older adults: results from the Baltimore longitudinal study of aging. *Age and Ageing* 44 (3), 485-490.

Koepsell, T. D., Wolf, M. E., Buchner, D. M., Kukull, W. A., LaCroix, A. Z., et al. 2004. Footwear style and risk of falls in older adults. *Journal of the American Geriatrics Society* 52 (9), 1495-1501.

Kraemer, W. J., Bush, J. A., Newton, R. U., Duncan, N. D., Volek, J. S., et al. 1998. Influence of a compression garment on repetitive power output production before and after different types of muscle fatigue. *Sports Medicine, Training and Rehabilitation* 8 (2), 163-184.

Kunzler, M. R., Lopes, L. M., Ueda, L. S., de Britto, M. A. & Carpes, F. P. 2013. Does skin stimulation compensate impairments in postural control after ankle plantar flexors fatigue? *Gait & Posture* 37 (4), 611-614.

Kuster, M. S., Grob, K., Kuster, M., Wood, G. A. & Gächter, A. 1999. The benefits of wearing a compression sleeve after ACL reconstruction. *Medicine and Science in Sports and Exercise* 31 (3), 368-371.

Lacour, M., Bernard-Demanze, L. & Dumitrescu, M. 2008. Postural control, aging, and attention resources: Models and posture-analysis methods. *Neurophysiologie Clinique* 38 (6), 411-421.

Lajoie, Y. & Gallagher, S. P. 2004. Predicting falls within the elderly community: comparison of postural sway, reaction time, the Berg balance scale and the Activities-specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. *Archives of Gerontology and Geriatrics* 38 (1), 11-26.

Larsen, L. E., Jakobsen, L. A., Jensen, A., Lambden, B. M., Sørensen, M. R., et al. 2015. Inhibition of soleus Hoffmann reflex by ankle–foot orthosis application in healthy volunteers. *Prosthetics and Orthotics International* 39 (6), 444-453.

Le Clair, K. & Riach, C. 1996. Postural stability measures: What to measure and for how long. *Clinical Biomechanics (Bristol, Avon)* 11 (3), 176-178.

Lee, Y. G., Kim, S. C., Chang, M., Nam, E., Kim, S. G., et al. 2018. Complications and socioeconomic costs associated with falls in the elderly population. *Annals of Rehabilitation Medicine* 42 (1), 120-129.

Long, Z., Wang, R., Han, J., Waddington, G., Adams, R., et al. 2016. Optimizing ankle performance when taped: Effects of kinesiology and athletic taping on proprioception in full weight-bearing stance. *Journal of Science and Medicine in Sport* 20 (3), 236-240.

Lord, S. R., Clark, R. D. & Webster, I. W. 1991. Postural stability and associated physiological factors in a population of aged persons. *Journal of Gerontology* 46 (3), M69-M76.

Losa Iglesias, M. E., Becerro de Bengoa Vallejo, Ricardo & Palacios Peña, D. 2012. Impact of soft and hard insole density on postural stability in older adults. *Geriatric Nursing* 33 (4), 264.

Lowrey, C. R., Strzalkowski, N. D. J. & Bent, L. R. 2010. Skin sensory information from the dorsum of the foot and ankle is necessary for kinesthesia at the ankle joint. *Neuroscience Letters* 485 (1), 6-10.

Ma, C. C., Lee, Y., Chen, B. & Aruin, A. S. 2016. Immediate and short-term effects of wearing a single textured insole on symmetry of stance and gait in healthy adults. *Gait & Posture* 49, 190-195.

Madhavan, S. & Shields, R. 2005. Influence of age on dynamic position sense: evidence using a sequential movement task. *Experimental Brain Research* 164 (1), 18-28.

Magalhães, F. & Kohn, A. 2014. Effectiveness of electrical noise in reducing postural sway: A comparison between imperceptible stimulation applied to the anterior and to the posterior leg muscles. *European Journal of Applied Physiology* 114 (6), 1129-1141.

Magalhães, F. & Kohn, A. 2012. Imperceptible electrical noise attenuates isometric plantar flexion force fluctuations with correlated reductions in postural sway. *Experimental Brain Research* 217 (2), 175-186.

Maki, B. E., Perry, S. D., Norrie, R. G. & Mcllroy, W. E. 1999. Effect of facilitation of sensation from plantar foot-surface boundaries on postural stabilization in young and older adults. *Journal of Gerontology* 54A (6), M281-M287.

Marques, A., Silva, A., Oliveira, A., Cruz, J., Machado, A., et al. 2017. Validity and relative ability of 4 balance tests to identify fall status of older adults with Type 2 Diabetes. *Journal of Geriatric Physical Therapy* 40 (4), 227-232.

Martínez, L., Pérez, T., Mirasso, C. & Manjarrez, E. 2007. Stochastic resonance in the motor system: effects of noise on the monosynaptic reflex pathway of the cat spinal cord. *Journal of Neurophysiology* 97 (6), 4007-4016.

Massion, J. 1994. Postural control system. *Current Opinion in Neurobiology* 4 (6), 877-87.

Masui, T., Hasegawa, Y., Matsuyama, Y., Sakano, S., Kawasaki, M., et al. 2005. Gender differences in platform measures of balance in rural community-dwelling elders. *Archives of Gerontology and Geriatrics* 41 (2), 201-209.

Maurer, C., Mergner, T., Bolha, B. & Hlavacka, F. 2001. Human balance control during cutaneous stimulation of the plantar soles. *Neuroscience Letters* 302 (1), 45-48.

McKeon, P. O., Booi, M. J., Branam, B., Johnson, D. L. & Mattacola, C. G. 2010. Lateral ankle ligament anesthesia significantly alters single limb postural control. *Gait & Posture* 32 (3), 374-377.

Melzer, I., Kurz, I. & Oddsson, L. I. E. 2010. A retrospective analysis of balance control parameters in elderly fallers and non-fallers. *Clinical Biomechanics* 25 (10), 984-988.

Menant, J. C., Steele, J. R., Menz, H.,B.Menz., Munro, B. J. & Lord, S. R. 2008. Optimizing footwear for older people at risk of falls. *Journal of Rehabilitation Research & Development* 45 (8), 1167-1182.

Menz, H. B., Lord, S. R. & Fitzpatrick, R. C. 2006. A tactile stimulus applied to the leg improves postural stability in young, old and neuropathic subjects. *Neuroscience Letters* 406 (1-2), 23-26.

Meyer, P., Oddsson, L. & De Luca, C. 2004. The role of plantar cutaneous sensation in unperturbed stance. *Experimental Brain Research* 156 (4), 505-512.

Michael, J., Dogramaci, S., Steel, K. & Graham, K. 2014. What is the effect of compression garments on a balance task in female athletes? *Gait & Posture 39* (2), 804.

Mirelman, A., Herman, T., Brozgol, M., Dorfman, M., Sprecher, E., et al. 2012. Executive function and falls in older adults: new findings from a five-year prospective study link fall risk to cognition. *PLoS One* 7 (6), e40297.

Miyoshi, T., Nozaki, D., Sekiguchi, H., Kimura, T., Sato, T., et al. 2003. Somatosensory graviception inhibits soleus H-reflex during erect posture in humans as revealed by parabolic flight experiment. *Experimental Brain Research* 150 (1), 109-113.

Moghadam, M., Ashayeri, H., Salavati, M., Sarafzadeh, J., Taghipoor, K. D., et al. 2011. Reliability of center of pressure measures of postural stability in healthy older adults: Effects of postural task difficulty and cognitive load. *Gait & Posture* 33 (4), 651-655.

Moreland, J. D., Richardson, J. A., Goldsmith, C. H. & Clase, C. M. 2004. Muscle weakness and falls in older adults: A systematic review and meta-analysis. *Journal of the American Geriatrics Society* 52 (7), 1121-1129.

Morris, S. & DeShon, R. P. 2002. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods* 7 (1), 105-125.

Moscufo, N., Guttmann, C. R. G., Meier, D., Csapo, I., Hildenbrand, P. G., et al. 2009. Brain regional lesion burden and impaired mobility in the elderly. *Neurobiology of Aging* 32 (4), 646-654.

Muir, S. W., Berg, K., Chesworth, B., Klar, N. & Speechley, M. 2010. Balance impairment as a risk factor for falls in community-dwelling older adults who are high functioning: a prospective study. *Physical Therapy* 90 (3), 338-347.

Muir, S. W., Gopaul, K. & Montero Odasso, M. M. 2012. The role of cognitive impairment in fall risk among older adults: A systematic review and meta-analysis. *Age and Ageing* 41 (3), 299-308.

Mynark, R. G. & Koceja, D. M. 2002. Down training of the elderly soleus H reflex with the use of a spinally induced balance perturbation. *Journal of Applied Physiology* 93 (1), 127-133.

Nashner, L. M., Black, F. O. & Wall, C. 1982. Adaptation to altered support and visual conditions during stance: Patients with vestibular deficits. *Journal of Neuroscience* 2 (5), 536-544.

Négyesi, J., Mobark, A., Zhang, L. Y., Hortobagyi, T. & Nagatomi, R. 2018. An above-knee compression garment does not improve passive knee joint position sense in healthy adults. *PLoS One* 13 (9), e0203288.

Nishikawa, T. & Grabiner, M. D. 1999. Peroneal motoneuron excitability increases immediately following application of a semirigid ankle brace. *The Journal of Orthopaedic and Sports Physical Therapy* 29 (3), 168-176.

O'Connor, D. W., Pollitt, P. A., Hyde, J. B., Fellows, J. L., Miller, N. D., et al. 1989. The reliability and validity of the mini-mental state in a British community survey. *Journal of Psychiatric Research* 23 (1), 87-96.

Oie, K. S., Kiemel, T. & Jeka, J. J. 2002. Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture. *Cognitive Brain Research* 14 (1), 164-176.

Olchowik, G., Tomaszewski, M., Olejarz, P., Warchoł, J., Różańska-Boczula, M., et al. 2015. The human balance system and gender. *Acta of Bioengineering and Biomechanics* 17 (1), 69.

Orth, D., Davids, K., Wheat, J., Seifert, L., Liukkonen, J., et al. 2013. The role of textured material in supporting perceptual-motor functions. *PLoS One* 8 (4), e60349.

Ozer, D., Senbursa, G., Baltaci, G. & Hayran, M. 2009. The effect on neuromuscular stability, performance, multi-joint coordination and proprioception of barefoot, taping or preventative bracing. *The Foot* 19 (4), 205-210.

Palluel, E., Nougier, V. & Olivier, I. 2008. Do spike insoles enhance postural stability and plantar-surface cutaneous sensitivity in the elderly? *AGE* 30 (1), 53-61.

Palluel, E., Olivier, I. & Nougier, V. 2009. The lasting effects of spike insoles on postural control in the elderly. *Behavioral Neuroscience* 123 (5), 1141-1147.

Palm, H., Brattinger, F., Stegmueller, B., Achatz, G., Riesner, H., et al. 2012. Effects of knee bracing on postural control after anterior cruciate ligament rupture. *The Knee* 19 (5), 664.

Papadopoulos, E. S., Nikolopoulos, C., Badekas, A., Vagenas, G., Papadakis, S. A., et al. 2007. The effect of different skin-ankle brace application pressures on quiet single-limb balance and electromyographic activation onset of lower limb muscles. *BMC Musculoskeletal Disorders* 8 (1), 89.

Patel, M., Fransson, P. A., Lush, D. & Gomez, S. 2008. The effect of foam surface properties on postural stability assessment while standing. *Gait & Posture* 28 (4), 649-656.

Pedroso, R. V., de Melo Coelho, F., Santos-Galduroz, R. F., Riani Costa, J. L., Gobbi, S., et al. 2011. Balance, executive functions and falls in elderly with Alzheimer's Disease (AD): a longitudinal study. *Archives of Gerontology and Geriatrics* 54 (2), 348-351.

Pelliccioni, G., Piloni, V., Sabbatini, D., Fioravanti, P. & Scarpino, O. 2014. Sex differences in pudendal somatosensory evoked potentials. *Techniques in Coloproctology* 18 (6), 565-569.

Perry, S. D., Radtke, A., McIlroy, W. E., Fernie, G. R. & Maki, B. E. 2008. Efficacy and effectiveness of a balance-enhancing insole. *The Journals of Gerontology: Series A, Biological Sciences and Medical Sciences* 63 (6), 595-602.

Peterka, R. J. 2002. Sensorimotor integration in human postural control. *Journal of Neurophysiology* 88 (3), 1097-1118.

Piirtola, M. & Era, P. 2006. Force platform measurements as predictors of falls among older people – A review. *Gerontology* 52 (1), 1-16.

Preszner-Domjan, A., Nagy, E., Szíver, E., Feher-Kiss, A., Horvath, G., et al. 2012. When does mechanical plantar stimulation promote sensory re-weighing: Standing on a firm or compliant surface? *European Journal of Applied Physiology* 112 (8), 2979-2987.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G. & Myklebust, B. M. 1996. Measures of postural steadiness: Differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering* 43 (9), 956-966.

Proske, U. & Gandevia, S. C. 2012. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiological Reviews* 92 (4), 1651-1697.

Qiu, F., Cole, M. H., Davids, K. W., Hennig, E. M., Silburn, P. A., et al. 2013. Effects of textured insoles on balance in people with Parkinson's disease. *PLoS One* 8 (12), e83309.

Qiu, F., Cole, M. H., Davids, K. W., Hennig, E. M., Silburn, P. A., et al. 2012. Enhanced somatosensory information decreases postural sway in older people. *Gait & Posture* 35 (4), 630-635.

Qu, X. 2015. Impacts of different types of insoles on postural stability in older adults. *Applied Ergonomics* 46 (PA), 38-43.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., et al. 2005. Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. Cerebral Cortex (New York, N.Y. : 1991) 15 (11), 1676-1689.

Ribeiro, F. & Oliveira, J. 2007. Aging effects on joint proprioception: the role of physical activity in proprioception preservation. *European Review of Aging and Physical Activity* 4 (2), 71-76.

Richardson, J. T. E. 2011. Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review* 6 (2), 135-147.

Riley, M. A. & Clarrk, S. 2003. Recurrence analysis of human postural sway during the sensory organization test. *Neuroscience Letters* 342 (1-2), 45-48.

Riva, D., Mamo, C., Fanì, M., Saccavino, P., Rocca, F., et al. 2013. Single stance stability and proprioceptive control in older adults living at home: gender and age differences. *Journal of Aging Research* 2013, 561695.

Robbins, S. & Waked, E. 1997. Foot position awareness: The effect of footwear on instability, excessive impact, and ankle spraining. *Critical Reviews in Physical and Rehabilitation Medicine* 9 (1), 53-74.

Robbins, S., Waked, E. & McClaran, J. 1995. Proprioception and stability: foot position awareness as a function of age and footwear. *Age and Ageing* 24 (1), 67.

Robbins, S., Waked, E. & Rappel, R. 1995. Ankle taping improves proprioception before and after exercise in young men. *British Journal of Sports Medicine* 29 (4), 242-247.

Robertson, S., Kremer, P., Aisbett, B., Tran, J. & Cerin, E. 2017. Consensus on measurement properties and feasibility of performance tests for the exercise and sport sciences: a Delphi study. *Sports Medicine - Open* 3 (1), 1-10.

Robertson, S., Robertson, S., Burnett, A., Burnett, A., Cochrane, J., et al. 2014. Tests examining skill outcomes in sport: A systematic review of measurement properties and feasibility. *Sports Medicine* 44 (4), 501-518.

Rose, D. 2010. Fallproof! : a comprehensive balance and mobility training program. (2nd edition) Champaign, IL: Human Kinetics.

Rose, S. & Guskiewicz, K. 2006. Effect of coordination training with and without Stochastic Resonance stimulation on dynamic postural stability of subjects with functional ankle instability and subjects with stable ankles. *Clinical Journal of Sport Medicine* 16 (4), 323-328.

Ross, S. E. 2007. Noise-enhanced postural stability in subjects with functional ankle instability. *British Journal of Sports Medicine* 41 (10), 656-659.

Ross, S. E., Arnold, B. L., Blackburn, J. T., Brown, C. N. & Guskiewicz, K. M. 2007. Enhanced balance associated with coordination training with Stochastic Resonance stimulation in subjects with functional ankle instability: An experimental trial. *Journal of Neuroengineering and Rehabilitation* 4 (1), 47.

Ross, S. E., Linens, S. W., Wright, C. J. & Arnold, B. L. 2013. Customized noise-stimulation intensity for bipedal stability and unipedal balance deficits associated with functional ankle instability. *Journal of Athletic Training* 48 (4), 463-470.

Ross, S. & Arnold, B. 2012. Noise-enhanced dynamic single leg balance in subjects with functional ankle instability. *Journal of Sport and Health Science* 1 (2), 102-106.

Saverino, A., Waller, D., Rantell, K., Parry, R., Moriarty, A., et al. 2016. The role of cognitive factors in predicting balance and fall risk in a neuro-rehabilitation setting. *PLoS One* 11 (4), e0153469.

Scott, V., Votova, K., Scanlan, A. & Close, J. 2007. Multifactorial and functional mobility assessment tools for fall risk among older adults in community, home-support, long-term and acute care settings. *Age and Ageing* 36 (2), 130-139.

Seeman, T. E., Huang, M., Bretsky, P., Crimmins, E., Launer, L., et al. 2005. Education and APOE-e4 in longitudinal cognitive decline: MacArthur studies of successful aging. *The Journals of Gerontology: Series B, Psychological Sciences and Social Sciences* 60 (2), 74-83.

Seigle, B., Ramdani, S. & Bernard, P. L. 2009. Dynamical structure of center of pressure fluctuations in elderly people. *Gait & Posture* 30 (2), 223-226.

Sejdić, E. & Lipsitz, L. A. 2013. Necessity of noise in physiology and medicine. *Computer Methods and Programs in Biomedicine* 111 (2), 459-470.

Sekizawa, K., Sandrey, M. A., Ingersoll, C. D. & Cordova, M. L. 2001. Effects of shoe sole thickness on joint position sense. *Gait & Posture* 13 (3), 221-228.

Shaffer, S. W. & Harrison, A. L. 2007. Aging of the somatosensory system: A translational perspective. *Physical Therapy* 87 (2), 193-207.

Shumway-Cook, A., Baldwin, M., Polissar, N. L. & Gruber, W. 1997. Predicting the probability for falls in community-dwelling older adults. *Physical Therapy* 77 (8), 812-819.

Shumway-Cook, A. & Horak, F. B. 1986. Assessing the influence of sensory interaction on balance: Suggestion from the field. *Physical Therapy* 66 (10), 1548-1550.

Simoneau, G. G., Degner, R. M., Kramper, C. A. & Kittleson, K. H. 1997. Changes in ankle joint proprioception resulting from strips of athletic tape applied over the skin. *Journal of Athletic Training* 32 (2), 141-147.

Simoneau, G. G., Ulbrecht, J. S., Derr, J. A. & Cavanagh, P. R. 1995. Role of somatosensory input in the control of human posture. *Gait & Posture* 3 (3), 115-122.

Sperlich, B., Born, D., Swarén, M., Kilian, Y., Geesmann, B., et al. 2013. Is leg compression beneficial for alpine skiers? *BMC Sports Science, Medicine and Rehabilitation* 5 (1), 18.

Stern, K. A. & Gottschall, J. S. 2012. Altering footwear type influences gait during level walking and downhill transitions. *Journal of Applied Biomechanics* 28 (5), 481-490.

Stevenson, T. J., Connelly, D. M., Murray, J. M., Huggett, D. & Overend, T. 2010. Threshold Berg balance scale scores for gait-aid use in elderly subjects: A secondary analysis. *Physiotherapy Canada* 62 (2), 133-140.

Stoukides, J., Holzer, C., Ritzau, J. & Burbank, P. 2006. Health Issues of Frail Older Adults. In P. M. Burbank (Ed.) Vulnerable Older Adults- Health Care Needs and Interventions. New York: Springer Publishing.

Suetterlin, K. J. & Sayer, A. A. 2014. Proprioception: where are we now? A commentary on clinical assessment, changes across the life course, functional implications and future interventions. *Age and Ageing* 43 (3), 313-318.

Tangen, G. G., Engedal, K., Bergland, A., Moger, T. A. & Mengshoel, A. M. 2014. Relationships between balance and cognition in patients with subjective cognitive impairment, mild cognitive impairment, and Alzheimer disease. *Physical Therapy* 94 (8), 1123-1134.

Taube, W., Gruber, M. & Gollhofer, A. 2008. Spinal and supraspinal adaptations associated with balance training and their functional relevance. *Acta Physiologica* 193 (2), 101-116.

Taylor, M. E., Delbaere, K., Lord, S. R., Mikolaizak, A. S. & Close, J. C. T. 2013. Physical impairments in cognitively impaired older people: implications for risk of falls. *International Psychogeriatrics* 25 (1), 148-56.

Thorbahn, B. & Newton, R. 1996. Use of the Berg balance test to predict falls in elderly persons. *Physical Therapy* 76 (6), 576-583.

Tinetti, M. E., Baker, D. I., McAvay, G., Claus, E. B., Garrentt, P., et al. 1994. A multifactorial intervention to reduce the risk of falling among elderly people living in the community. *New England Journal of Medicine* 331 (13), 821-827.

Tomomitsu, M. S. V., Alonso, A. C., Morimoto, E., Bobbio, T. G. & Greve, J. M. D. 2013. Static and dynamic postural control in low-vision and normal-vision adults. *Clinics (Sao Paulo, Brazil)* 68 (4), 517-521.

Truter, I. 2011. Falls prevention in the elderly. *South African Pharmaceutical Journal* 78 (9), 12-17.

Tsai, Y. & Lin, S. 2013. Older adults adopted more cautious gait patterns when walking in socks than barefoot. *Gait & Posture* 37 (1), 88-92.

Tucker, M. G., Kavanagh, J. J., Morrison, S. & Barrett, R. S. 2010. Differences in rapid initiation and termination of voluntary postural sway associated with ageing and falls-risk. *Journal of Motor Behavior* 42 (5), 277-287.

Van Tiggelen, D., Coorevits, P. & Witvrouw, E. 2008. The effects of a neoprene knee sleeve on subjects with a poor versus good joint position sense subjected to an isokinetic fatigue protocol. *Clinical Journal of Sport Medicine* 18 (3), 259-265.

Vuillerme, N. & Pinsault, N. 2007. Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue. *Experimental Brain Research* 183 (3), 323-327.

Waddington, G. & Adams, R. 2003. Football boot insoles and sensitivity to extent of ankle inversion movement. *British Journal of Sports Medicine* 37 (2), 170.

Waked, E., Robbins, S. & McClaran, J. 1997. The effect of footwear midsole hardness and thickness on proprioception and stability in older men. *Journal of Testing and Evaluation* 25 (1), 143-148.

Wang, C., Hsieh, C., Olson, S. L., Wang, C., Sheu, C., et al. 2006. Psychometric properties of the Berg balance scale in a community-dwelling elderly resident population in Taiwan. *Journal of the Formosan Medical Association* 105 (12), 992-1000.

Wayland, L., Holt, L., Sewell, S., Bird, J. & Edelman, L. 2010. Reducing the patient fall rate in a rural health system. *Journal for Healthcare Quality : official publication of the National Association for Healthcare Quality* 32 (2), 9-15.

Westlake, K. P. & Culham, E. G. 2006. Influence of testing position and age on measures of ankle proprioception. *Advances in Physiotherapy* 8 (1), 41-48.

Wheat, J. S., Haddad, J. M., Fedirchuk, K. & Davids, K. 2014. Effects of textured socks on balance control during single-leg standing in healthy adults. *Procedia Engineering* 72, 120-125.

Whitney, J., Close, J. C. T., Lord, S. R. & Jackson, S. H. D. 2012. Identification of high risk fallers among older people living in residential care facilities: a simple screen based on easily collectable measures. *Archives of Gerontology and Geriatrics* 55 (3), 690-695.

Wilson, M. L., Rome, K., Hodgson, D. & Ball, P. 2008. Effect of textured foot orthotics on static and dynamic postural stability in middle-aged females. *Gait & Posture* 27 (1), 36-42.

Winter, D. A. 1995. Human balance and posture control during standing and walking. *Gait & Posture* 3 (4), 193-214.

Wong, T., Nguyen, H. V., Chiu, M. T., Chow, K. Y., Ong, M. E. H., et al. 2015. The low fall as a surrogate marker of frailty predicts long-term mortality in older trauma patients. *PLoS One* 10 (9), e0137127.

Woo, M. T., Davids, K., Liukkonen, J., Chow, J. Y. & Jaakkola, T. 2017a. Falls, cognitive function, and balance profiles of Singapore community-dwelling elderly individuals: Key risk factors. *Geriatric Orthopaedic Surgery & Rehabilitation* 8 (4), 256-262.

Woo, M. T., Davids, K., Liukkonen, J., Jaakkola, T. & Chow, J. Y. 2014. Effects of textured compression socks on postural control in physically active elderly individuals. *Procedia Engineering* 72, 162-167.

Woo, M. T., Davids, K., Liukkonen, J., Orth, D., Chow, J. Y., et al. 2017b. Effects of different lower-limb sensory stimulation strategies on postural regulation - A systematic review and meta-analysis. *PLoS One* 12 (3), e0174522 .

Wu, K. H., Ng, Y. F. & Mak, F. T. 2001. Effects of knee bracing on the sensorimotor function of subjects with anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine* 29 (5), 641-645.

Yeo, Y. Y. C., Lee, S. K., Lim, C. Y., Quek, L. S. & Ooi, S. B. S. 2009. A review of elderly injuries seen in a Singapore emergency department. *Singapore Medical Journal* 50 (3), 278-283.

You, S. H. 2005. Joint position sense in elderly fallers: a preliminary investigation of the validity and reliability of the SENSERite measure. *Archives of Physical Medicine and Rehabilitation* 86 (2), 346-352.

You, S. H., Granata, K. P. & Bunker, L. K. 2004. Effects of circumferential ankle pressure on ankle proprioception, stiffness, and postural stability: A preliminary investigation. *The Journal of Orthopaedic and Sports Physical Therapy* 34 (8), 449-460.

APPENDICES

APPENDIX 1

Principal Investigator: Assoc. Professor Chow Jia Yi

Co-Principal Investigator: Ms. Woo Mei Teng

NIE's COPY
Please sign and return to school.

An examination of the effects of compression socks in postural control across elderly individuals.

Dear Participant,

You are invited to participate in a research study that will scan your general well-being, falls history medical conditions and balance ability. If you meet the criteria of the subsequent phase of the study, examination on your postural balance (Static and dynamic tasks) and proprioception will be conducted in the laboratory.

Aim of Study

The aim of this study are to i) undertake an empirical evaluation of elderly individual's risk of falling in Singapore, and ii) examine the effect of wearing compression socks in postural control and stability of elderly individuals when performing everyday actions involving proprioception, static and dynamic balancing tasks.

The information from this study will provide information on the prevalence and the risk factors of falls in Singapore, and gain greater insights on the effects of a compression footwear, particularly socks on postural control and stability in elderly individuals. We are writing to ask permission to include you in this study.

Procedures

This study consists of two phases – screening phase (phase 1) and experimental phase (phase 2). For phase 1, three hundred and eighty four (384) mobile elderly individuals age 65 years and above, without any muscular, neurological and cardiovascular diseases, and who are free from stroke and brain injuries will be recruited from community centres in Singapore. For phase 2, sixty (60) participants who meet the inclusion criteria will be randomly selected from phase 1.

APPENDIX 2

Form 3.1

The Health/Activity Questionnaire Used in the *FallProof!* Program

Date ____________________

Name ____________________ Address ____________________

____________________ City ____________________ State ________ Zip ________

Home Phone # ____________________ Gender: Male ________ Female ________

Age ____________ Year of birth ____________ Height ____________ Weight ____________

Ethnicity ____________________ Highest level of education completed ____________________

Whom to contact in a case of emergency ____________________ Phone # ____________

Name of your physician ____________________ Phone # ____________

1. Have you ever been diagnosed as having any of the following conditions?

	Yes (X)	Year of onset (approximate)
Heart attack	☐	________
Transient ischemic attack	☐	________
Angina (chest pain)	☐	________
High blood pressure	☐	________
Stroke	☐	________
Peripheral vascular disease	☐	________
Diabetes	☐	________
Neuropathies (problems with sensations)	☐	________
Respiratory disease	☐	________
Parkinson's disease	☐	________
Multiple sclerosis	☐	________
Polio/post polio syndrome	☐	________
Epilepsy/seizures	☐	________
Other neurological conditions	☐	________
Osteoporosis	☐	________
Rheumatoid arthritis	☐	________
Other arthritic conditions	☐	________
Visual/depth perception problems	☐	________
Inner ear problems/recurrent ear infections	☐	________
Cerebellar problems (ataxia)	☐	________
Other movement disorders	☐	________
Chemical dependency (alcohol and/or drugs)	☐	________
Depression	☐	________

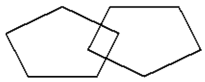
(continued)

APPENDIX 3

Mini-Mental State Examination (MMSE)

Patient's Name: ____ Date: _____________

***Instructions:** Ask the questions in the order listed. Score one point for each correct response within each question or activity.*

Maximum Score	Patient's Score	Questions
5		"What is the year? Season? Date? Day of the week? Month?"
5		"Where are we now: State? County? Town/city? Hospital? Floor?"
3		The examiner names three unrelated objects clearly and slowly, then asks the patient to name all three of them. The patient's response is used for scoring. The examiner repeats them until patient learns all of them, if possible. Number of trials: ___________
5		"I would like you to count backward from 100 by sevens." (93, 86, 79, 72, 65, …) Stop after five answers. Alternative: "Spell WORLD backwards." (D-L-R-O-W)
3		"Earlier I told you the names of three things. Can you tell me what those were?"
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		"Repeat the phrase: 'No ifs, ands, or buts.'"
3		"Take the paper in your right hand, fold it in half, and put it on the floor." (The examiner gives the patient a piece of blank paper.)
1		"Please read this and do what it says." (Written instruction is "Close your eyes.")
1		"Make up and write a sentence about anything." (This sentence must contain a noun and a verb.)
1		"Please copy this picture." (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.) 
30		TOTAL

(Adapted from Rovner & Folstein, 1987)

Source: www.medicine.uiowa.edu/igec/tools/cognitive/MMSE.pdf Provided by NHCQF, 0106-410

APPENDIX 4

Berg Balance Scale

SITTING TO STANDING
INSTRUCTIONS: Please stand up. Try not to use your hand for support.
( ) 4 able to stand without using hands and stabilize independently
( ) 3 able to stand independently using hands
( ) 2 able to stand using hands after several tries
( ) 1 needs minimal aid to stand or stabilize
( ) 0 needs moderate or maximal assist to stand

STANDING UNSUPPORTED
INSTRUCTIONS: Please stand for two minutes without holding on.
( ) 4 able to stand safely for 2 minutes
( ) 3 able to stand 2 minutes with supervision
( ) 2 able to stand 30 seconds unsupported
( ) 1 needs several tries to stand 30 seconds unsupported
( ) 0 unable to stand 30 seconds unsupported

If a subject is able to stand 2 minutes unsupported, score full points for sitting unsupported. Proceed to item #4.

SITTING WITH BACK UNSUPPORTED BUT FEET SUPPORTED ON FLOOR OR ON A STOOL
INSTRUCTIONS: Please sit with arms folded for 2 minutes.
( ) 4 able to sit safely and securely for 2 minutes
( ) 3 able to sit 2 minutes under supervision
( ) 2 able to able to sit 30 seconds
( ) 1 able to sit 10 seconds
( ) 0 unable to sit without support 10 seconds

STANDING TO SITTING
INSTRUCTIONS: Please sit down.
( ) 4 sits safely with minimal use of hands
( ) 3 controls descent by using hands
( ) 2 uses back of legs against chair to control descent
( ) 1 sits independently but has uncontrolled descent
( ) 0 needs assist to sit

TRANSFERS
INSTRUCTIONS: Arrange chair(s) for pivot transfer. Ask subject to transfer one way toward a seat with armrests and one way toward a seat without armrests. You may use two chairs (one with and one without armrests) or a bed and a chair.
( ) 4 able to transfer safely with minor use of hands
( ) 3 able to transfer safely definite need of hands
( ) 2 able to transfer with verbal cuing and/or supervision
( ) 1 needs one person to assist
( ) 0 needs two people to assist or supervise to be safe

STANDING UNSUPPORTED WITH EYES CLOSED
INSTRUCTIONS: Please close your eyes and stand still for 10 seconds.
( ) 4 able to stand 10 seconds safely
( ) 3 able to stand 10 seconds with supervision
( ) 2 able to stand 3 seconds
( ) 1 unable to keep eyes closed 3 seconds but stays safely
( ) 0 needs help to keep from falling

STANDING UNSUPPORTED WITH FEET TOGETHER
INSTRUCTIONS: Place your feet together and stand without holding on.
( ) 4 able to place feet together independently and stand 1 minute safely
( ) 3 able to place feet together independently and stand 1 minute with supervision
( ) 2 able to place feet together independently but unable to hold for 30 seconds
( ) 1 needs help to attain position but able to stand 15 seconds feet together
( ) 0 needs help to attain position and unable to hold for 15 seconds

APPENDIX 5

Characteristic of included studies

Lower limbs' stimulation strategies	Study	Study Design	Equipment	Comparison	Outcome
Wearable garments	Birmingham et al. (2001)	Repeated measures	Force platform (AMTI model OR6-5)	Brace vs no brace treatments	A significant main effect for the brace condition. Knee brace improved the control of single-limb standing balance +ve
	Broglio et al. (2009)	Repeated measures	Balance Error Scoring System (BESS) NeuroCom Sensory Organisation Test (SOT)	Barefoot vs prophylactic ankle taping vs laced bracing treatments	Ankle taping and laced bracing had negative influence on BESS postural control performance before and after a 20-min walk. -ve
	Cavanaugh et al. (2016)	Repeated measures	Y Balance Test; 50cm drop jump landing (dominant leg)	Kinesiology tape vs Knee Compression stocking vs control Fatigue vs non-fatigue conditions	There was no statistically different among the treatment conditions - kinesiology tapes, compression sleeves and control on balance tasks performance. ~
	Genthon et al. (2010)	Mixed-design	Force platform (PF02, Equi+, Aix les Bains)	Barefoot vs compression stocking (15-20mmhg) vs orthosis (internal elastic taping) treatments	Ankle orthosis reduced the postural instability of ankle sprain patients. The mean resultant CoP trajectories amplitude was reduced during compression stocking. +ve
	Gribble et al. (2010)	Repeated measures	Force platform (Bertec)	Brace vs no brace treatments	There was no significant influence of the selected ankle brace on the Resultant vector of time-to-stabilisation (RVTTS) in single-limb landing balance task. -ve
	Hadadi et al (2011)	Mixed-design	Force platform (Bertec)	Healthy adult vs Functional ankle instability (FAI) patients	Interaction of foot and brace significant in the FAI group not the healthy group. +ve

				No-brace vs soft vs semi-rigid treatments Injured vs non-injured limb	A significant effect of brace was found only for the injured limb. +ve Decreased in postural sway in FAI group especially in soft brace condition. +ve Postural sway increased from no-brace condition to soft then to semi-rigid orthoses.+ve
	Hadadi et al (2014)	Mixed-design	Star Excursion Balance Test (SEBT)	Healthy vs Functional ankle instability (FAI) No-brace vs soft vs semi-rigid treatments Injured vs non-injured limb	Ankle orthoses improved reach distance in FAI patients in various reach directions. +ve
	Hijmans et al. (2009)	Mixed-design	Foot pressure plate (Rsscan Footscan) Modified Slope box Pressure monitoring device	No compression bandage vs compression bandage class II (23-32 mmhg) treatments	Balance deteriorated in older participants with the application of compression. -ve Joint position sense improved significantly in older participants as a result of the application of compression. +ve
Wearable garments	Kunzler et al. (2013)	Repeated measures	3-D force plate (OR6 2000, Advanced Mechanical Technology)	No-tape vs tape treatment Fatigue vs non-fatigues conditions	Tape improved postural control in the non-fatigue condition as shown in the decrease of CoP velocity and CoP amplitude. +ve
	Kuster et al. (1999)	Repeated measures	Force platform (Kistler)	Non-compression sleeve vs elastic compression sleeve treatment	A 10% increase of peak ground contact forces when wearing compression sleeves. +ve A significant reduction was observed in the path length of the CoP (indicating improved steadiness). +ve A compression sleeve seems capable of compensating for the loss of proprioception and muscle coordination after

					ACL rupture or reconstruction by compressing the skin, muscles and tendons. +ve
	Michael et al. (2014)	Repeated measures	Force platform (Kistler) Motion Analysis System (Vicon)	Conventional shorts vs loose-fitted compression garment vs well-fitted compression garments treatments	By wearing the well-fitted compression garment significantly improved balance time and significantly decreased postural sway variability compared with conventional shorts in the eyes closed condition. +ve Compression garments had no effect on static balance when vision was present. -ve
	Ozer et al. (2009)	Repeated measures	Chronometer Functional squat system machine	Barefoot vs preventive brace (Aircast) vs prophylactic tape treatments	There was no significant difference among the treatments for balance test. -ve
	Palm et al. (2012)	Repeated measures	Biodex stability system - dynamic posturography tests	No-brace vs brace treatment Injured vs non-injured limb	Knee brace improved significantly the overall stability index (OSI) for injured leg. +veˆ No significant difference for the non-injured leg. -ve
	Papadopoulos et al. (2007)	Repeated measures	Tekscan Mat	No-brace vs brace with 30kPa pressure vs brace with 60kPa pressure treatments.	Ankle brace treatments (30 & 60kPa pressure) resulted in a deterioration of the anteroposterior CoP excursion and excursion velocity, both with open and closed eyes. -ve
	Sperlich et al. (2013)	Repeated measures	Moving platform (Posturomed)	No compression garment vs 20 mmhg compression garment vs 40 mmhg compression garment treatments.	No significant effect on single leg standing balance on the moving platform. -ve Compression garments in the range of 20-30mmhg may improve alpine skiing performance by allowing a deeper tuck position and lowering perceived exertion. +ve

	Vuillerme & Pinsault (2007)	Repeated measures	Force platform (PF01, Equi+, Aix les Bains)	No tactile vs tactile (wide strips) treatment Non-fatigue vs fatigue conditions	Strips of athletic tape reduced the CoP surface area in both non-fatigue and fatigue conditions. +ve
Wearable garments	Wheat et al. (2014)	Repeated measures	Force platform (Kistler)	socks with no nodules vs nodules on the plantar surface vs nodules on the dorsal surface vs nodules at the side of the foot vs nodules for the entire surface	There was no statistically significant effect of adding texture to socks at any location on balance during single-legged standing in young, healthy adults. Results revealed a trend towards improved balance in the Sides sock condition. ~
	Woo et al. (2014)	Repeated measures	Force platform (Kistler)	Barefoot vs commercial socks vs compression socks	There were no significant main effects for the lightly-textured compression socks in postural control. -ve
Textured Materials	Aruin & Kaneka. (2013)	Repeated measures	SMART EquiTest System (NeuroCom International) GAITRite system	No insole vs right D-insole vs left D-insole	Significant immediate effect of the textured insole was seen in the outcome measures of static (weight bearing) and dynamic (weight symmetry index, strength symmetry) balance tests as well as in gait symmetry (single support and swing phases). +ve
	Collings et al. (2015)	Repeated measures	Plantar pressure measurement system (Fscan, Teskcan)6 Telemetry unit (MT8)	No dowels insoles vs 2mm dowels insoles vs 4mm dowels insoles vs 6mm dowels insoles	The rate of CoP change was greater while wearing the lateral zoned insoles. This suggest that the site of stimulation of the plantar foot may increase postural instability during walking. ~
	Corbin et al. (2007)	Repeated measures	Accusway Plus Balance platform (Advanced Mechanical Technology)	Non-textured vs textured insoles	Postural control improved while subjects wore textured insoles during bilateral, eyes-closed stance. +ve There was no significant main effect for texture insoles in unilateral stance balancing task. -ve

	Hatton et al. (2009)	Repeated measures	Force platform (Kistler) BIOPAC EMG system	Control insoles vs texture 1 (small pyramidal peaks) vs textured 2 (larger convex circular pattern	There was no significant effect of the two textured surfaces on postural balance. -ve
	Hatton et al. (2011)	Repeated measures	Force platform (Kistler) BIOPAC EMG system	Control insoles (smooth) vs texture 1 (Evalite Pyramid EVA) vs textured 2 (nora Lunasoft Mini Non Slip)	Textured surfaces can improve ML sway in older people. A significant decrease in Medio-lateral range with eyes closed was observed when standing on texture 1. +ve
	Hatton et al. (2012)	Repeated measures	Force platform (Kistler) GAITRite instrumentation (CIR system)	Control insoles (smooth) vs textured insoles	There was no significant difference of the textured insole on standing balance. -ve Textured insole leads to a significant reduction in gait velocity, step length and stride length. +ve
	Ma et al. (2016)	Repeated measures	Balance Master1 system (NeuroCom International, USA). GaitRite1 walkway	Single insoles vs no insole	There was no significant difference of the textured insole on the gait velocity and cadence.~ Asymmetry of stance and gait was observed immediately the implementation of the single textured insole. ~
	Maki et al. (1999)	Repeated measures	Horizontal translation of a computer-controlled, movable platform.	No tubing vs flexible polyethylene tubing	The facilitation (flexible polyethylene tubing) affected the responses of healthy young adults, as well as older subjects, high- lights the potent influence of these receptors. ~ Flexible polyethylene tubing appeared to improve control of stepping and postural reactions evoked by the continuous-perturbation platform. +ve Flexible polyethylene tubing decreased backward CoP excursion in feet-in-place response. +ve

	Menz et al. (2006)	Mixed-Design	Optical displacement device (MEL Mikro-elektronik, M5L/200)	No tactile stimulus vs tactile stimulus (Velcro) to the ankle vs tactile stimulus to the calf vs tactile stimulus to the knee	Passive tactile stimulus applied to the skin of the leg significantly reduces postural sway in healthy young subjects, older subjects without diabetic peripheral neuropathy and diabetic peripheral neuropathy patients. +ve
	Palluel et al. (2008)	Mixed-design	Force platform (PF01, Equi+, Aix les Bains)	Non-spike insoles vs spike insoles	Spike insoles contributed to the improvement of unperturbed stance in the elderly with relatively intact plantar cutaneous sensation. +ve Standing or walking for 5 min lead to a significant improvement of balance in both elderly and young adults. For elderly, the effects were more pronounced in the standing than in the walking session. +ve
Textured Materials	Palluel et al. (2009)	Mixed-design	Force platform (PF01, Equi+, Aix les Bains)	Non-spike insoles vs spike insoles	Spike stimulation enhanced the somatosensation. The artificial sensory message elicited by the spikes improve postural control in both elderly and younger groups. +ve
	Perry et al. (2008)	Mixed-design	Motion-analysis system (Optotrak 3020)	Conventional insoles vs facilitatory insoles (raised ridge)	The facilitatory insole improved lateral stability during gait. +ve Facilitatory-insole group appeared to reduce the fall rate. +ve
	Qiu et al. (2012)	Mixed-design	Force platform (HUR Labs OY, Finland)	Barefoot vs hard textured insole surface (320 density ethhylenevinyl acetate) vs soft textured insole surface	The older group benefitted from the use of different insoles surfaces (hard & soft) on C90 area sway. +ve There was a significant and progressive decrease in path length from the barefoot to hard and to soft insole surface. +ve Both hard and soft insoles decrease the

					AP and ML sway for the older group when standing on foam surfaces. +ve
	Qu (2015)	Repeated measures	Force platform (OR6-7, AMTI)	Cupped insoles vs textured insoles vs rigid insoles vs soft insoles	Static postural stability was not affected by the selected insoles. -ve Textured insoles did not improve static and dynamic balance. -ve
	Stern & Gottschall (2012)	Repeated measures	3D photogrammetric system (Motion Analysis Corporation) Wire amplifier system (Bortec Octopus AMT-8)	Regular insoles vs foam (Dr.Scholl's 2X Air Pillow insoles) vs textured vs barefoot vs Iced barefoot	Footwear conditions alter gait patterns. ~ There was not enough evidence to support that textured insoles improve dynamic balance. ~
	Wilson et al. (2008)	Mixed-design	Force platform (Kistler) GAITRite instrumentation (CIR system)	Control insoles vs Plain and smooth surface insoles vs dimpled surface insoles vs raised grid pattern insoles	No significant results were found. When shoe type is standardized there is no detrimental effect of postural ability over a 4-week period of intervention in the middle-age women using foot orthotic with differently textured surfaces. -ve
Stochastic Resonance	Amiridis et al. (2005)	Mixed-Design	Force platform (Kistler)	No electrostimulation vs electrostimulation (20-70mA)	CoP maximum displacement in anterio-posterior and mediolateral directions significantly decreased after electrostimulation training. +ve A reduction in anterioposterior sway. +ve
	Collins et al. (2011)	Repeated measures	Force platform	No electrical stimulation and no sleeve (1) vs no electrical stimulation with sleeve vs 75% electrical stimulation with sleeve vs 150% electrical stimulation with sleeve vs no electrical stimulation and no sleeve (2)	No significant differences were found in the study measures between the testing conditions. -ve The SR electrical stimulation did not produce significant improvements in balance relative to the sleeve-alone condition. -ve

	Dickstein et al. (2005)	Repeated measures	Force platform (AMTI)	Non-transcutaneous electrical nerve stimulation (TENS) vs Bilateral TENS vs TENS Left vs TENS Right	Application of TENS at threshold amplitudes to the posterior aspect of the calves reduces postural sway velocity (Decrease of 5%). +ve
	Gravelle et al. (2002)	Repeated measures	Forceplate (Kistler 9286)	No electrical noise vs electrical noise(Gaussian white)	Overall improvement in balance performance in the electrical noise stimulation condition. +ve Three of the sway parameters (ML SD; AP Max; Path Length) decreased significantly in the electrical noise stimulation condition. +ve
	Kimura & Kouzaki (2013)	Repeated measures	Force platform (EFP-S- 1.5kNSA13B)	No electrical stimulation vs electrical stimulation (white-noise-like, frequency 5-1000hz)	Postural sway reduced during quiet bipedal stance for electrical stimulation group. The average amplitude, the peak-to-peak amplitude, the SD of CoP(A/p) significantly decreased by 7.7%, 8.9% and 8.4% respectively. +ve
	Magalhaes & Kohn (2011)	Repeated measures	Force platform (AMTI)	No electrical stimulation vs electrical stimulation (white-noise) to tibialis anterior (TA) vs electrical stimulation to triceps surae (TS) vs electrical stimulation to TA & TS	Electrical noise applies bilaterally over the TS muscles reduces postural oscillations during bipedal quiet stance. +ve There was a significant correlation between the reduction in force fluctuation and the decrease in postural sway due to the electrical noise stimulation. +ve
Stochastic Resonance	Magalhaes & Kohn (2014)	Repeated measures	Force platform (AMTI)	No electrical stimulation vs electrical stimulation (white-noise, 0.90ST) to tibialis anterior (TA) vs electrical stimulation to triceps surae (TS) vs electrical stimulation to TA & TS	Subsensory electrical noise applied to the anterior or posterior leg muscles significantly reduced postural sway measures when compared to control condition. +ve

	Ross (2007)	Repeated measures	Force platform (Bertec)	No stochastic resonance (SR) stimulation vs SR stimulation (0.05mA or 0.01mA)	Optimal SR stimulation improved postural stability of functional ankle instability (FAI) group compared to the control condition. Significant reduction in centre-of-pressure velocities- resultant (COPV-R). +ve
	Ross & Arnold (2012)	Repeated measures	Force platform (Bertec)	No stochastic resonance (SR) stimulation vs SR stimulation (0.05mA)	Stochastic resonance stimulation improved dynamic single leg balance by reducing anterioposterior Time-to-stabilisations (TTS) in FAI participants. +ve
	Ross & Guskiewicz (2006)	Mixed-Design	Force platform (Bertec)	Coordination training vs SR stimulation (0.05mA) and coordination training.	SR stimulation might improve dynamic postural stability more quickly than coordination training for FAI participants. ~
	Ross et al. (2007)	Mixed-Design	Force platform (Bertec)	No stochastic resonance (SR) stimulation and coordination training vs coordination training vs SR stimulation (0.05mA) and coordination training.	SR stimulation used as an adjunct therapy to coordination training enhanced postural stability deficits associated with FAI. +ve Stochastic resonance and coordination training group had lower CoP velocity in AP and ML directions. +ve
	Ross et al. (2013)	Mixed-Design	Accusway Plus Balance platform (Advanced Mechanical Technology)	0% SR stimulation vs 25% SR stimulation vs 50% SR stimulation vs 75% SR stimulation vs 90% SR stimulation	Customized optimal intensity significantly improved double-leg standing balance in both FAI and healthy groups. +ve

+ve favor intervention; -ve favor control; ~ neutral

ORIGINAL PAPERS

I

EFFECTS OF DIFFERENT LOWER-LIMB SENSORY STIMULATION STRATEGIES ON POSTURAL REGULATION – A SYSTEMATIC REVIEW AND META-ANALYSIS

by

Woo, M. T., Davids, K., Liukkonen, J., Orth, D., Chow, J. Y., & Jaakkola, T. 2017

PLoS ONE 12(3): e0174522.

https://doi.org/10.1371/journal.pone.0174522

PLOS | ONE

RESEARCH ARTICLE

Effects of different lower-limb sensory stimulation strategies on postural regulation—A systematic review and meta-analysis

Mei Teng Woo[1,2]*, Keith Davids[3], Jarmo Liukkonen[1], Dominic Orth[4], Jia Yi Chow[5], Timo Jaakkola[1]

1 Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland, **2** School of Sports, Health and Leisure, Republic Polytechnic, Singapore, Singapore, **3** Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, United Kingdom, **4** Faculty of Behavioral and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, Netherland, **5** Physical Education and Sports Science, National Institute of Education, Nanyang Technological University, Singapore, Singapore

* woo_mei_teng@rp.edu.sg

Citation: Woo MT, Davids K, Liukkonen J, Orth D, Chow JY, Jaakkola T (2017) Effects of different lower-limb sensory stimulation strategies on postural regulation—A systematic review and meta-analysis. PLoS ONE 12(3): e0174522. https://doi.org/10.1371/journal.pone.0174522

Editor: David J Clark, University of Florida, UNITED STATES

Received: November 28, 2016

Accepted: March 10, 2017

Published: March 29, 2017

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: The author(s) received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Abstract

Systematic reviews of balance control have tended to only focus on the effects of single lower-limb stimulation strategies, and a current limitation is the lack of comparison between different relevant stimulation strategies. The aim of this systematic review and meta-analysis was to examine evidence of effects of different lower-limb sensory stimulation strategies on postural regulation and stability. Moderate- to high- pooled effect sizes (Unbiased (Hedges' *g*) standardized mean differences (SMD) = 0.31–0.66) were observed with the addition of noise in a Stochastic Resonance Stimulation Strategy (SRSS), in three populations (i.e., healthy young adults, older adults, and individuals with lower-limb injuries), and under different task constraints (i.e., unipedal, bipedal, and eyes open). A Textured Material Stimulation Strategy (TMSS) enhanced postural control in the most challenging condition—eyes-closed on a stable surface (SMD = 0.61), and in older adults (SMD = 0.30). The Wearable Garments Stimulation Strategy (WGSS) showed no or adverse effects (SMD = -0.68–0.05) under all task constraints and in all populations, except in individuals with lower-limb injuries (SMD = 0.20). Results of our systematic review and meta-analysis revealed that future research could consider combining two or more stimulation strategies in intervention treatments for postural regulation and balance problems, depending on individual needs.

Introduction

During human postural control, individuals constantly regulate movements, subconsciously, based on perceived information to achieve postural stability. In the past two decades, many studies have been devoted to investigating effects of lower-limb sensory stimulation strategies (e.g. tapes/sleeves/ braces/compression; application of Stochastic Resonance; textured insoles and footwear) for postural regulation and balance performance in different populations. Common to intervention strategies is the assumption that lower-limb stimulation increases somatosensory feedback. Specifically, it has been proposed that increasing attunement to plantar cutaneous afferent information sent to the Central Nervous System (CNS) [1,2] enhances balance/postural regulation by supporting faster detection of, and/or responses to, postural sway [3–7]. Studies have shown that cutaneous afference plays an important role in maintenance of balance [3,8–11]. Kavounoudias et al. [8] suggested that plantar cutaneous afference from the soles of the feet could potentially provide valuable feedback for balance regulation. They interpreted the sole of each foot as having a "dynamometric map", where numerous sensors of the sole are able to spatially organise different pressures exerted against it, providing information to regulate balance and posture. Hence, plantar cutaneous afferents provide valuable feedback to the balance control system making it an important mechanism in supporting the functionality of the somatosensory system overall. Here we sought to examine evidence of the effects of different lower-limb sensory stimulation strategies on postural regulation and stability in order to contrast their relative effectiveness.

To the best of our knowledge, no published article has focused on the comparison of the effects of various lower-limb stimulation strategies such as tapes, braces, compression garments, textured insoles and footwear, and application of added random sub-threshold electrical or mechanical stimulation (noise) (exploiting a mechanism referred to as Stochastic Resonance [SR]). To date, systematic reviews have tended to only focus on a single stimulation strategy such as the role of textured materials [12], shoes and ankle appliances [3] and ankle taping and bracing [13]. Two of these studies quantified the review in a meta-analysis [12,13]. These studies have provided an overview of the effects of specific lower-limb stimulation strategies on balance control, but have been limited in not comparing the relevance of different stimulation strategies. A systematic review and meta-analysis of the entire body of work on lower-limb stimulation strategies will provide much-needed insights on the relevance of each stimulation strategy and its influence on postural regulation during static and dynamic balancing tasks. This information would inform clinicians, physiotherapists, practitioners, rehabilitation therapists and sport and exercise scientists about the relative effectiveness of each stimulation strategy.

The specific purposes of this review article are: i) to review systematically the effects of lower-limb stimulation strategies on sensory regulation of postural control and balance performance ii) to meta-analyze the effect of these lower-limb stimulation strategies on various populations (healthy young adults; older adults; individuals with lower-limb injuries) and under different task constraints (unipedal; bipedal; eyes open; eyes-closed).

Previous evidence of efficacy of different lower-limb stimulation strategies: Wearable Garments (WG), Textured Materials (TM) and application of Stochastic Resonance (SR)

Wearable Garments (WG). The main focus of early research using wearable garments (e.g., tapes, braces and compression garments) was related to injury and re-injury prevention [14–16]. Investigations centred on how disrupted proprioception could be enhanced by using wearable garments. For example, two studies investigated effects of strips and athletic tapes on joint movement position awareness [15,16] for injury prevention. Robbins et al. [15] suggested that the traction of the tape on the skin provided cutaneous sensory cues of plantar surface position to enhance anticipation of the foot position before contact with the floor. Similarly, effects of wearing compression garments (shorts and sleeves) on joint position sense [17] and postural regulation and balance during a single-leg landing task [14] were also tested. Kuster et al. [14] revealed that the compressive sleeve intervention reduced postural sway in the anteroposterior (AP) direction. It was argued that wearable garments such as tapes, compression garments, and braces could improve proprioception, specifically on improving judgment of ankle position and orientation of the plantar surface with respects to the leg [16, 18].

Furthermore, Kraemer et al. [17] suggested that it was possible that cutaneous receptors interacted with compression garment fabric, and that the signals may be even more important in fatigued musculature as evidenced by the test garments' enhancement of performance in a fatigued jump task. They suggested that compression might interact with a biological cueing system to enhance performance. Following these promising findings, a number of research programmes have since examined the utility of different approaches for achieving improved performance outcomes, ostensibly via similar mechanisms. Such interventions have included: tapes [19–21], braces [22–24] and compression garments [25–27] in young, healthy adults and people with lower-limb injuries (e.g., Functional Ankle Instability (FAI)).

Michael [28] suggested that compression shorts improved the total time in unipedal standing balance in a more challenging condition involving visual occlusion. For young athletes with lower extremity injuries, studies have shown that compression via orthoses and sleeves improved uni- and bipedal balance performance [25,29–31] and proprioception [14, 20]. However, Papadapoulos et al. [24] suggested that ankle braces with 30kPa and 60kPa pressure were not able to alter the balance control strategy of the central nervous system (CNS). In an elderly sample, localized compression on the ankle was shown to improve joint position sense, but not a static balance performance [26]. Thus, mixed findings exist on the role of wearing compression garments, compared to control conditions of wearing non-compression garments on postural regulation.

Textured Materials (TM). Textured materials, especially textured insoles, have also emerged as an important research area in somatosensory intervention studies. Texture insoles are deemed to be beneficial because they increase the sensitivity of plantar cutaneous afferent information sent to the CNS [1]. The systematic review by Hijmans et al. [3] suggested that insoles with tubing or vibrating elements might improve balance. However, no definitive conclusions have been drawn on effects of such insoles on balance in older people (> 60 years old) and patients with peripheral nervous system disorders. In a later meta-analysis carried out by Orth and colleagues, it was concluded that simple stimulation of cutaneous receptors via added texture can improve perceptual-motor system functionality in elderly individuals as well as in young, healthy adults. Several studies have suggested a positive relationship between balance/postural regulation and somatosensory feedback provided by use of textured insoles [4,5,7,32]. Qiu and colleagues [7] suggested that textured insole surfaces, both hard and soft, reduced postural sway during standing in older people. At the same time, Losa lglesias and colleagues [5] also reported that hard insole surfaces may be more effective compared to soft insole surfaces for reducing fall risk. Losa lglesias et al. [5] concluded that more rigid insoles promoted a more neutral alignment of the talocrural joint in a standing position, limiting the range of foot pronation, thereby, improving the ankle joint stability.

Stochastic Resonance (SR). In addition to wearable garments and textured insoles, the use of sub-threshold electrical or mechanical stimulation (white noise) for stimulating soles of the feet, known as application of SR, has also received substantial research attention. Various studies introducing sub-sensory electrical or mechanical noise to enhance postural regulation were conducted between 2002 to 2014 (e.g., Collins et al. [33]). They examined effects of various intensities of electrical noise on balance control in FAI patients [34–36], older adults [37,38] young and healthy adults [39–42]. The majority of these studies found significant improvements in postural regulation during the performance of static and dynamic balancing tasks. These findings suggested that stimulation, through added noise, boosted detection of sensorimotor signals through SR, subsequently enhancing functioning of the postural regulation system. Sejdic & Lipsitz [43] stated that people who lost the resiliency and adaptive capacity due to aging and diseases, the postural regulation system can be restored by exploiting the phenomenon of SR.

From the motor system perspective, two studies highlighted the potential benefits of introducing SR in the motor systems of humans and cats [44,45]. Cordo et al. [44] showed how introduction of weak input signals (non-zero level of noise) through the tendon of a parent muscle enhanced the sensitivity of the muscle spindle receptors. This stimulation increased the muscle spindle sensory outputs to modulate performance in complex motor tasks (e.g., for balance). Martínez et al. [45] tested the effects of noise on the monosynaptic reflect pathway of the cat spinal cord. Their study showed that an application of SR could increase the sensitivity of motor neurons and that mechanical noise could be employed to improve feline motor task performance.

The majority of the reviewed studies showed promising findings on effects of individual lower-limb stimulation strategy on postural regulation systems. This quantified review seeks to provide new insights on this area of work with specific focus on the heterogeneity, similarities and differences between intervention strategies in enhancing postural regulation systems.

Method

Search strategy

The search and reporting format were conducted in accordance with the PRISMA statement (S1 PRISMA Checklist) [46]. Electronic databases (EBSCO, Science Direct, PubMed, Taylor and Francis, Google Scholar, and Scopus) were searched to identify publications concerning the effects of different lower- limb stimulation strategies (tapes/braces/sleeves, textured materials, and application of Stochastic Resonance) on postural regulation and stability. A detailed literature search identified articles published in English between 1995 and October 2016. An additional hand-conducted search of reference lists was undertaken to identify studies not captured in the electronic database searches. The following combination of two groups of keywords was used in searching relevant articles:

1. Lower-limb stimulation strategies: "Textured/Textured insoles or footwear", "Compression/Compression garments and stocking", "Tapes and braces", "Application of Stochastic Resonance/ added noise."
2. Task- related: "Postural Control" and "Balance."

Selection of studies

The first reviewer (lead author) performed the search of the electronic databases and screened the potentially relevant articles based on abstracts and titles at the initial screening. Then, the retrieved articles were evaluated separately by the first and fourth authors using the following inclusion and exclusion criteria for full review, with any disagreement resolved by consensus.

Inclusion Criteria:

1. No restrictions on study design.
2. Studies published in English between 1995 and October 2016.
3. Studies investigating the effects of behavioural measures of textured materials (insoles; stocking), wearable garments (compression garments; braces; tapes), and application of

Stochastic Resonance during tasks involving postural stability and balance (static; dynamic) in non-fatigue conditions.

4. The primary outcome measures consisted of the center of pressure (CoP) related measurements, the center of mass (CoM), distance reach, balance time, and gait variables.
5. The primary outcomes included in the meta-analysis were the center of pressure (CoP) related measurements such as CoP sway and standard deviations (SD) in medial-lateral (ML), and anterior-posterior (AP) directions; path length; recurrence quantification analysis (RQA) measurements.
6. In the meta-analysis, studies were required to report means and standard deviations of outcome measures interacting with lower-limb stimulation strategies.

Exclusion Criteria:

1. Studies that use cumbersome and expensive equipment in investigating vibration effects on postural ability, which is more complex and costly for end-users, compared to the simpler addition of electrical stimulation, textured, and wearable materials. Furthermore, vibration effects usually produce stimulation above the consciously perceived threshold level, which would negate the role of Stochastic Resonance in enhancing proprioception and haptic perception at a sub-threshold level.
2. Studies where outcome variables are not compatible for comparison, (means and standard deviations) in the meta-analysis.
3. Studies in stroke, diseases resulting in neuropathy (e.g. Multiple Sclerosis and Parkinson Disease) and cerebral palsy populations, with some damage to the brain, impairing physical mobility and postural control mechanisms.

Lower-limb stimulation strategies

In this context of study, three main groups of the lower-limb stimulation strategies were based on the characteristics—wearable garments, textured materials, and an application of stochastic resonance. Compression garments (sleeves; socks), braces and tapes were grouped as Wearable Garments (WGSS). Textured insoles and footwear were grouped as Textured Materials (TMSS). Last, implementation of white noise and electrical stimulation were grouped as an application of Stochastic Resonance (SRSS).

Assessment of methodological quality

The methodological quality of the included studies was assessed by two reviewers (lead author and the fourth author) using the Cochrane Collaborations tool for evaluating the risk of bias [47]. The domains of assessment were sequence generation, allocation concealment, blinding of participants, personnel and outcome assessors, incomplete outcome data, selective outcome reporting and other sources of bias. Summary outcomes of all studies for each domain were categorised as "low risk of bias", "high risk of bias" and "unclear risk of bias". Any discrepancies were resolved through consensus between the two reviewers.

Data extraction and management

For the systematic review, the extracted data included: sample size, participant characteristics, tasks, equipment used, balance-related measurements and main outcomes of the study. Only studies that reported the outcome measures of interest (CoP related measurements) were included in the statistical analysis. The CoP related data was used due to its commonality in postural control and regulation research [48]. Furthermore, Ruhe et al. [49] also suggested that 81.3% of the research studies demonstrated acceptable reliability levels of using CoP measures and it could be used as a reliable tool for investigating general postural stability and balance performance under specific conditions.

Analysis and meta-analytic techniques

The primary analysis was to compare the effectiveness of the three different lower-limb stimulation strategies—Wearable garments, Textured materials, and application of Stochastic Resonance. Unbiased (Hedges' *g*) standardized mean differences (SMD) and 95% confidence intervals (CI) were calculated for continuous outcomes [50]. In studies that investigated more than two treatments (e.g., compression socks and normal socks), the calculated effect size of the multiple treatments was combined and treated as a single effect size for each continuous outcome [51]. Five studies from WGSS [23,24,27,28,52], four studies from TMSS [7,53–55], and three studies from SRSS [33,39,56] had more than two treatments in the experimental design. All the effect sizes of the outcomes were then combined as a single effect size for each study. In the event of multiple stages of task design (pre- and post-conditioning procedures, for example), the most appropriate stage (pre- or post-treatment) was chosen, based upon its relevance to the objective of this analysis.

For dependent group designs, effect size estimates for lower-limb stimulation strategies for the control group in each study were standardized using the control group standard deviation value [12]. However, the pooled standard deviation was used as the denominator in independent group designs [51]. The value of rho estimates from Orth et al. [12] was used to compute the unbiased variance estimates. Subsequently, standard error (SE) of each study was calculated based on the computed unbiased variance estimates [51].

Calculated synthesized (by average) estimated effect size and standard error (SE) values were imported into Review Manager (RevMan computer program, version 5.3.5 Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) for the calculation of pooled effect size, p-value, z- value, Tau^2, heterogeneity (I^2). The following settings were used: data type—generic inverse variance; statistical method—inverse variance; analysis model—random effects; effect measure—standardized mean difference (SMD); study and total confidence interval– 95%. An effect size of 0.1 is considered small, an effect size of 0.3 is medium, and an effect size of 0.5, large [51].

Consequently, pooled effect size, 95% confidence interval, P-value and heterogeneity (I^2) were calculated per subgroup, per study. An alpha level of .05 (two-tailed) was used to test whether the average effect size was significantly different from zero in each subgroup.

Subgroup analysis. The subgroup analysis was used to derive pooled estimates of the three subgroups (WGSS; TMSS; SRSS) for the differences observed on postural control performances. Three main areas identified for subgroup comparison were: i) static balance tasks —single-leg standing (SLS) and double-limbs standing (DLS); ii) populations—young and healthy adults, older adults, lower-limb injuries individuals (e.g. Ankle sprained; Anterior Cruciate Ligament reconstruction; Knee Osteoarthritis); and iii) vision availability—eyes open and -closed. There is always some debate over the measurements of postural sway to express system stability. In the meta-analysis of this review, decreases in CoP measurements imply the increased ability of a postural-regulation system to maintain balance. Hence, a positive effect size indicated a functional role of stimulation strategies, while a negative effect size inferred that there was a positive functional capacity of the control group in regulating posture.

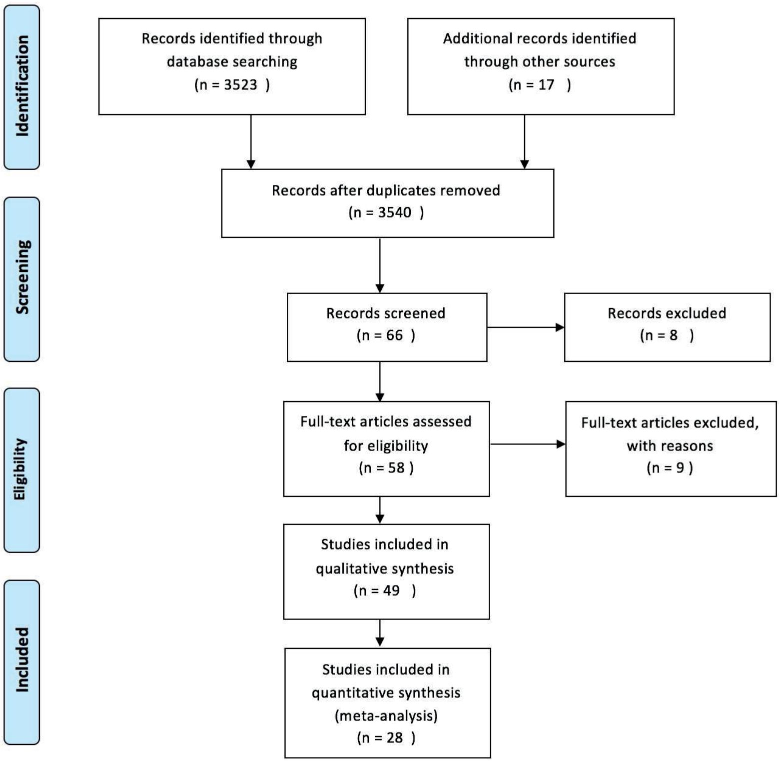


Fig 1. Summary of the search strategy and selection process based on included and excluded studies.

https://doi.org/10.1371/journal.pone.0174522.g001

Results

Study selection and characteristics

Fig 1 outlines the process of the literature review search. A total of 58 out of 3540 studies were identified, based on the title and abstract review from the electronic database and hand searches. Nine studies were excluded as the intervention treatments, or the measure outcomes did not match the inclusion criteria after the initial assessment.

Of the 49 studies (S1 Table), 18 examined the effects of the wearable garments stimulation strategy (WGSS), 19 investigated the effects of textured materials stimulation strategy (TMSS), and 12 studied the application of Stochastic Resonance stimulation strategy (SRSS). Thirty studies used a repeated measures design, with each participant performing in all the conditions (control and stimulation treatments). Seventeen studies used a mixed-model design, where they were two or more independent groups performing all the treatment conditions (S1 Table). Six studies used a pre, post-test protocol, where the intervention periods ranged from 5-minutes to 12-weeks, to measure the effects of lower-limb stimulation strategies [37,57–61]. One study, by Qu [62], was unique in that it did not specify a control condition to compare with the other textured insoles treatments.

A summary of the characteristics of all included studies was tabulated according to the three different lower-limb stimulation strategies and presented, based on participant characteristics (Table 1) and the assessment tasks (Table 2). In Table 1, the majority of studies (n = 28) involved young and healthy adults as research participants to examine the effect of the lower-limb strategies on static and dynamic balancing tasks. The second main population for

Table 1. Characteristic of included studies based on populations.

Lower limbs' strategies	Study	Young Healthy Adults	Middle-aged and older adults	Neuropathy patients	Athlete / Elite	Lower limbs' Injuries or medical condition	Remarks
Wearable Garments	Birmingham et al. (2001)					√	
	Broglio et al. (2009)	√					
	Cavanaugh et al. (2016)	√					
	Genthon et al. (2010)					√	
	Gribble et al. (2010)					√	
	Hadadi et al (2011)	√				√	
	Hadadi et al. (2014)	√				√	
	Hijmans et al. (2009)	√	√				
	Kunzler et al. (2013)	√					
	Kuster et al. (1999)					√	
	Michael et al. (2014)				√		
	Ozer et al. (2009)	√					
	Palm et al. (2012)					√	
	Papadopoulos et al. (2007)	√					
	Sperlich et al. (2013)				√		
	Vuillerme & Pinsault (2007)	√					
	Wheat et al. (2014)	√					
	Woo et al. (2014)		√				
Textured Materials	Aruin & Kaneka. (2013)	√					
	Collings et al. (2015)	√					
	Corbin et al. (2007)	√					
	Hatton et al. (2009)	√					
	Hatton et al. (2011)		√				
	Hatton et al. (2012)		√				
	Jenkins et al. (2009)		√	√ (PD)			
	Kelleher et al. (2010)	√		√ (MS)			
	Ma et al. (2016)	√					
	Maki et al. (1999)	√	√				
	Menz et al. (2006)	√	√	√			
	Palluel et al. (2008)	√	√				
	Palluel et al. (2009)	√	√				
	Perry et al. (2008)		√				
	Qiu et al. (2012)	√	√				
	Qiu et al. (2013)		√	√ (PD)			
	Qu (2015)		√				
	Stern & Gottschall (2012)	√					
	Wilson et al. (2008)		√ (middle-aged)				Mean age: 51.1±5.8

(*Continued*)

Table 1. (*Continued*)

Lower limbs' strategies	Study	Young Healthy Adults	Middle-aged and older adults	Neuropathy patients	Athlete / Elite	Lower limbs' Injuries or medical condition	Remarks
Stochastic Resonance	Amiridis et al. (2005)		√				
	Collins et al. (2012)		√			√ (Knee Osteoarthritis)	
	Dickstein et al. (2005)	√					
	Gravelle et al. (2002)		√				
	Kimura & Kouzaki (2013)	√					
	Magalhaes & Kohn (2012)	√					
	Magalhaes & Kohn (2014)	√					
	Ross (2007)					√	
	Ross & Arnold (2012)					√	
	Ross & Guskiewicz (2006)	√				√	
	Ross et al. (2007)					√	
	Ross et al. (2013)	√					

https://doi.org/10.1371/journal.pone.0174522.t001

the wearable garments' research included participants with some form of lower-limb injuries (n = 7). The textured material (n = 5) and application of Stochastic Resonance (n = 4) research studies focused on a middle/old age population.

From Table 2, the double-limb standing (DLS) balance tasks were the most commonly used tests in all studies (n = 24). Surprisingly, the single-leg standing (SLS) balance task has not been considered as the main assessment task in TMSS research. However, the TMSS grouping included the most number of studies in gait related tasks. Whereas, the wearable garments stimulation strategy (WGSS) grouping favored both static and dynamic balance tasks, specifically SLS. On the other hand, a majority of the studies in WGSS and SRSS examined only one task, while the TMSS grouping tended to include two or more tasks in a single study.

Risk of bias

Most studies in WGSS and TMSS groupings were at high risk of bias for selection bias, performance, and detection categories (Fig 2). Fig 3 depicts a funnel plot based on the 28 studies included in the meta-analysis on the effects of lower-limb stimulation strategies on postural control. The asymmetrical shape of this plot suggests possible reporting bias or low methodological quality of some studies [63].

Overall, about 67% of the studies (n = 33) met the criteria for high risk of bias in the sequence generation category. Of the 33 studies, SRSS had the least number of studies (n = 5; 15.2%) followed by TMSS (n = 11; 33.3%) and WGSS (n = 17; 51.5%). In the WGSS group, all 17 studies (100%) included a non-random approach for selection of participants. There were 24 studies meeting criteria for high risk of bias in the allocation concealment category. Of the 24 studies, 13 from WGSS (54.2%), 8 from TMSS (33.3%) and 3 from SRSS (12.5%).

With regards to the blinding categories, a high risk of bias was found in both the WGSS and TMSS groups– 13 (61.9%) and 6 (28.6%) out of 21 studies, respectively. However, it is

Table 2. Characteristic of included studies based on tasks constraints.

Lower limbs' strategies	Study	Static			Dynamic		Gait		
		SLS	DLS	Tandem Stance	Unstable/ moving platform (SLS); SEBT	Single leg land_Jump/hop	Stable	Uneven	Hill
Wearable Garments	Birmingham et al. (2001)	√***; √ ###				√			
	Broglio et al. (2009)	√*	√*	√*					
	Cavanaugh et al. (2016)				√ (SEBT)	√			
	Genthon et al. (2010)		√**						
	Gribble et al. (2010)					√			
	Hadadi et al (2011)	√*							
	Hadadi et al (2014)				√ (SEBT)				
	Hijmans et al. (2009)		√***						
	Kunzler et al. (2013)		√**						
	Kuster et al. (1999)					√			
	Michael et al. (2014)	√***							
	Ozer et al. (2009)	√							
	Palm et al. (2012)				√				
	Papadopoulos et al. (2007)	√***							
	Sperlich et al. (2013)				√				
	Vuillerme & Pinsault (2007)		√**						
	Wheat et al. (2014)	√***							
	Woo et al. (2014)		√***; √ ###						
Textured Materials	Aruin & Kaneka. (2013)		√*		√		√		
	Collings et al. (2015)						√		
	Corbin et al. (2007)	√***	√***						
	Hatton et al. (2009)		√*						
	Hatton et al. (2011)		√***						
	Hatton et al. (2012)		√***				√		
	Jenkins et al. (2009)						√		
	Kelleher et al. (2010)						√		
	Ma et al. (2016)						√		
	Maki et al. (1999)				√				
	Menz et al. (2006)		√***						
	Palluel et al. (2008)		√*				√		
	Palluel et al. (2009)		√*						
	Perry et al. (2008)							√	
	Qiu et al. (2012)		√***; √ ###						
	Qiu et al. (2013)		√***; √ ###						
	Qu (2015)		√***						
	Stern & Gottschall (2012)						√		√
	Wilson et al. (2008)		√***				√		

(*Continued*)

Table 2. (*Continued*)

Lower limbs' strategies	Study	Static			Dynamic		Gait		
		SLS	DLS	Tandem Stance	Unstable/ moving platform (SLS); SEBT	Single leg land_Jump/hop	Stable	Uneven	Hill
Stochastic Resonance	Amiridis et al. (2005)	√*	√*	√*					
	Collins et al. (2012)	√*							
	Dickstein et al. (2005)		√*						
	Gravelle et al. (2002)	√*							
	Kimura & Kouzaki (2013)		√**						
	Magalhaes & Kohn (2012)		√*						
	Magalhaes & Kohn (2014)		√**						
	Ross (2007)	√*							
	Ross & Arnold (2012)					√			
	Ross & Guskiewics. (2006)					√			
	Ross et al. (2007)	√*							
	Ross et al. (2013)	√*	√*						

* Vision: eyes open;
**Vision: eyes-closed;
***Vision: eyes open and closed;
Surface: stable;
Surface: stable and foam

https://doi.org/10.1371/journal.pone.0174522.t002

important to acknowledge the challenge faced when attempting to blind participants and researchers to intervention materials that are perceivable, especially in WGSS and TMSS groups.

In contrast, most studies (~75.5%) were at as low risk of bias in the participant attrition and reporting categories, with no missing outcome data, with all the relevant dependent variables apparently reported. However, two studies each from WGSS [26,30] and TMSS [59,64] groupings were at high risk of bias for incomplete outcome data. The reasons for this included: imbalanced numbers of participants across the groups [26,59], or because participants were excluded due to an additional injury [30], or reduced total sample sizes due to data corruption [64].

Eight studies were rated at a high risk of reporting bias because they failed to report the key outcomes or provided incomplete information on dependent variables [1,7,20,28,34,59,65,66]. The reasons for this were due to incomplete outcomes reported [7,28,65], and failure to include results for key outcomes [1,20,34,59,65].

Performance outcomes

Overall, a total of 30 studies (WGSS = 9; TMSS = 11; SRSS = 10) reported positive effects of applying lower-limb stimulation strategies on static balance tasks, dynamic balance tasks and gait (S1 Table). Five studies (WGSS = 1; TMSS = 3; SRSS = 1) concluded the findings with a neutral statement [61,67–70]. A study from WGSS reported mixed results, where they only

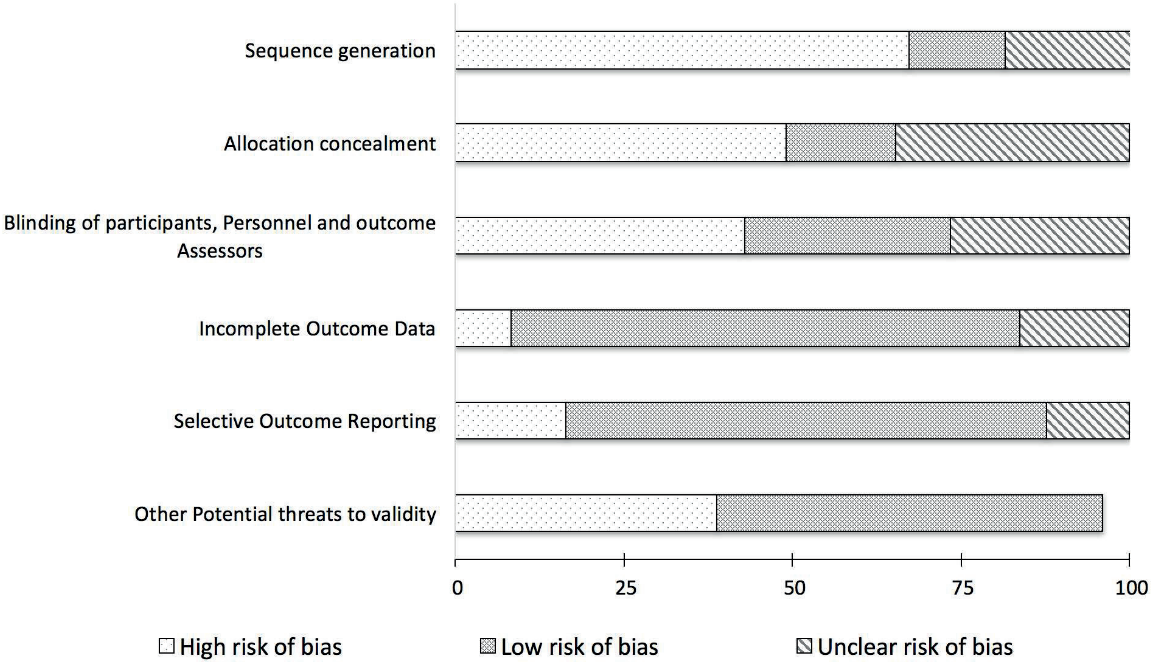


Fig 2. Risk of bias summary.

https://doi.org/10.1371/journal.pone.0174522.g002

found the beneficial effects in under specific constraints, including an eyes-closed condition [28]; and under a stability task performed by participants on an injured leg [22,23,25].

Wearable Garments Stimulation Strategy (WGSS). Of the 7 studies in this grouping, six found that braces, tapes and compression sleeves improved postural regulation especially in participants with lower-limb injuries [22,23,25,30,71]. There was only one study by Gribble et al. [65] reporting that an ankle brace did not affect the balance performance in a population with a lower-limb injury.

For the young and healthy adults, Kunzler et al. [72] and Vuillerme and Pinsault [21] indicated that taping treatment improved postural regulation in a non-fatigue condition, as shown in the decrease of CoP velocity and CoP surface area. In contrast, eight studies did not find it beneficial by applying the tapes or braces on the limbs of young and healthy adults [19,20,23,24,26,52,67,71].

There were two studies that reported no significant differences in postural regulation with compression bandages and stockings for older adults [26,27]. Two studies examined the effects of compression garments on postural regulation in athletes [28,66]. Sperlich et al. [66] concluded that no significant improvement in postural regulation with the compression garments in the eyes-closed condition, whereas, Michael et al. [28] found otherwise.

Textured Materials Stimulation Strategy (TMSS). A total of 10 studies examined TMSS effects on postural regulation in static and dynamic balance tasks in young and healthy adults. Five studies reported beneficial effects during performance in DLS balance tasks [1,57,58,73,74], four studies found no significant differences in postural regulation during double-limb standing [7,53] and in gait [69,75], and two suggested that the evidence was insufficient to arrive at a concrete conclusion for dynamic balance control (Gait) [68,70].

For middle-aged and older adults, 63.6% (7 out of 11) of the studies indicated that textured insoles had a positive influence on static balance control [7,54,57,58], dynamic balance control

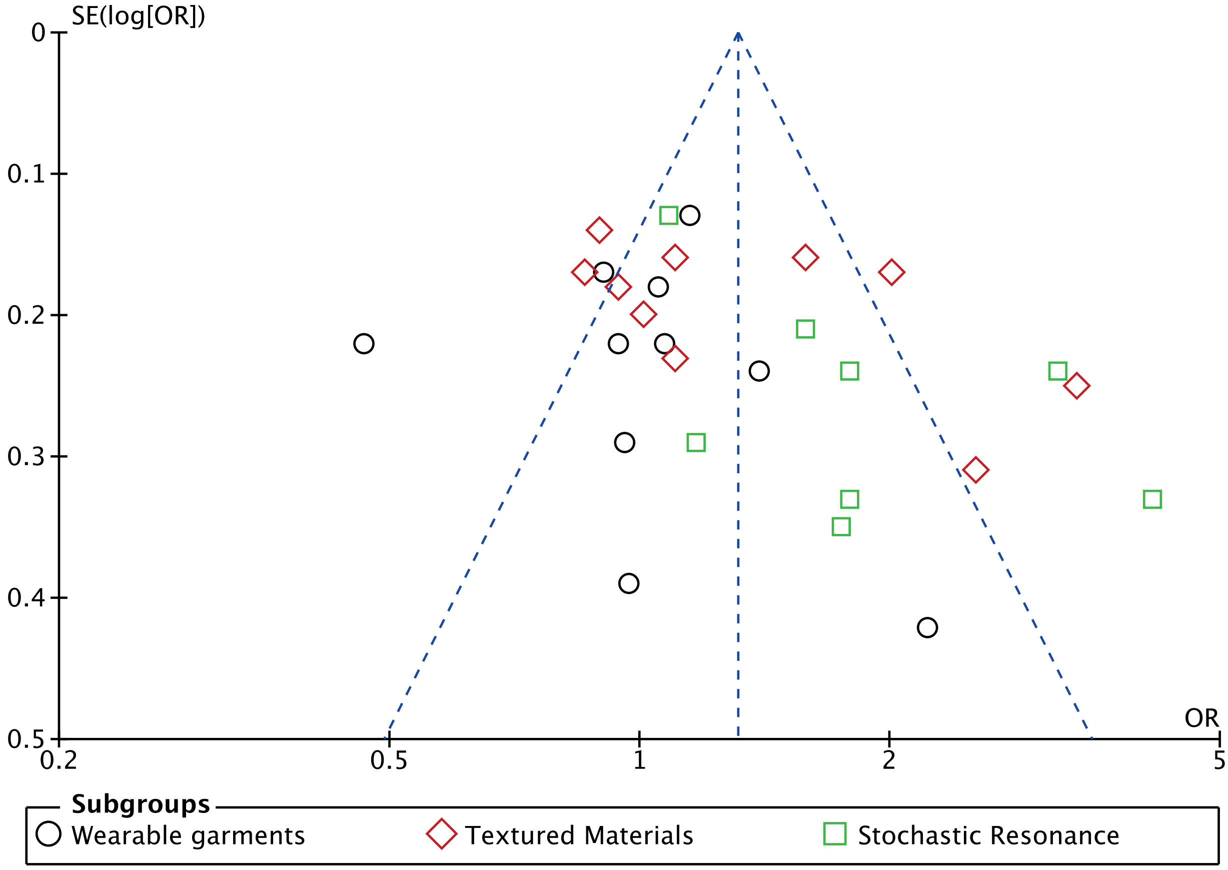


Fig 3. Funnel plot of all studies included in the meta-analysis.

https://doi.org/10.1371/journal.pone.0174522.g003

[74] and postural regulation in gait [59,64]. Three studies found no significant improvement or detrimental effects of using textured insoles on postural regulation during the double-limb standing tasks [55,60,62]. There was only one study showing no improvement in gait with the use of facilitatory ribbed insoles [76].

There was a unique study that examined the effects of using Velcro, an affordable and innovative approach to providing tactical stimulation, on three groups of participants—young and healthy adults, older adults, and diabetic peripheral neuropathy patients [56]. The Velcro was used to rub gently against the skin on the side of the ankle, calf and knee, instead of stimulating the soles of the feet. Findings revealed that the Velcro stimulus significantly reduced postural sway in all three groups of participants.

Application of Stochastic Resonance Stimulation Strategy (SRSS). Ten out of twelve studies (83.3%) concluded that application of SR had a significant effect on postural regulation in young and healthy adults [39–42,77], older participants [37,38], and participants with lower-limb injuries [34–36]. Positive effects were observed in static balance tasks [34,35,37–42,77] and a dynamic balance task (Single-leg landing task) [36].

Only one study did not find a significant improvement in performance on a single-leg standing task with sub-threshold electrical stimulation in older adults with minimal-to-moderate knee osteoarthritis [33]. On the other hand, Ross & Guskiewicz [61] postulated that application of SR stimulation might improve dynamic postural stability more quickly than coordination training for lower-limb injuries (Functional ankle instability) participants.

Meta-analysis

Among the included studies, 28 studies reported CoP measurement outcomes for the static balance tasks and were included in meta-analysis. The subgroups are wearable garments (n = 10), textured materials (n = 10) and application of SR (n = 8) as lower-limb stimulation strategies. For the static balance tasks, CoP measurements such as time-to-stabilization, path length, the postural sway velocity and distance in both Anterior-posterior (AP) and medial-lateral (ML) directions under the different vision (e.g., eyes open and closed) and surface (stable & foam) conditions were included in the analysis. For the sample populations (young and healthy adults, elderly individuals, and with lower-limb injuries), the CoP measurements from SLS and DLS under the stable surface condition with eyes open and -closed were included in the analysis. For the vision conditions, CoP measurements of all populations, which performed both SLS and DLS under the stable surface, were included in the analysis. Both SLS and DLS comprise popular experimental paradigms used by researchers. The reasons for their popularity could be due to the complex sensory information perceptual mechanisms used during upright stance. It could also due to the association between DLS and the risk of falling, especially in elderly population [78,79]. Single-leg standing was used to increase the difficulty of the standing task and also for a comparative examination of balance performance between the injured and non-injured legs.

Tasks: Single-Leg Standing (SLS) & Double-Limbs Standing (DLS). Ten studies (WGSS = 5; SRSS = 5) reported CoP measurements of postural regulation during performance of the SLS task (Fig 4). There was a significant difference between the two subgroups, WGSS and SRSS (p = 0.02), where a higher pooled effect size was observed in SRSS group (SMD = 0.49, z = 2.40, p = 0.02). However, there was a high level of heterogeneity observed in the SRSS (Tau^2 = 0.15; df = 4; I^2 = 76%) group compared to the homogeneity observed in the WGSS group (Tau^2 = 0.00; df = 4; I^2 = 0%). This finding indicated that 76% of variability between effect sizes of SRSS studies displayed a systematic influence of one or more variables. The average pooled effect size for the WGSS was found to be 0.20, which corresponds to a

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1.1.1 Wearable Garments							
Birmingham et al. 2001	0.05	0.18	30	30	11.6%	0.05 [−0.30, 0.40]	2001
Papadapoulos et al. 2007	−0.1	0.17	33	33	12.0%	−0.10 [−0.43, 0.23]	2007
Hadadi et al. 2011	0.07	0.22	20	20	10.1%	0.07 [−0.36, 0.50]	2011
Wheat et al. 2014	−0.04	0.29	13	13	7.9%	−0.04 [−0.61, 0.53]	2014
Michael et al. 2014	−0.06	0.22	20	20	10.1%	−0.06 [−0.49, 0.37]	2014
Subtotal (95% CI)			**116**	**116**	**51.8%**	**−0.02 [−0.20, 0.16]**	
Heterogeneity: Tau^2 = 0.00; Chi^2 = 0.58, df = 4 (P = 0.97); I^2 = 0%							
Test for overall effect: Z = 0.20 (P = 0.84)							
1.1.2 Stochastic Resonance							
Gravelle et al. 2002	0.16	0.29	13	13	7.9%	0.16 [−0.41, 0.73]	2002
Amiridis et al. 2005	1.42	0.33	21	21	6.8%	1.42 [0.77, 2.07]	2005
Ross 2007	0.58	0.24	11	10	9.4%	0.58 [0.11, 1.05]	2007
Collins et al. 2012	0.08	0.13	52	52	13.6%	0.08 [−0.17, 0.33]	2012
Ross et al 2013	0.46	0.21	24	24	10.5%	0.46 [0.05, 0.87]	2013
Subtotal (95% CI)			**121**	**120**	**48.2%**	**0.49 [0.09, 0.89]**	
Heterogeneity: Tau^2 = 0.15; Chi^2 = 16.42, df = 4 (P = 0.003); I^2 = 76%							
Test for overall effect: Z = 2.40 (P = 0.02)							
Total (95% CI)			**237**	**236**	**100.0%**	**0.21 [−0.00, 0.43]**	
Heterogeneity: Tau^2 = 0.07; Chi^2 = 24.42, df = 9 (P = 0.004); I^2 = 63%							
Test for overall effect: Z = 1.92 (P = 0.05)							
Test for subgroup differences: Chi^2 = 5.17, df = 1 (P = 0.02), I^2 = 80.7%							

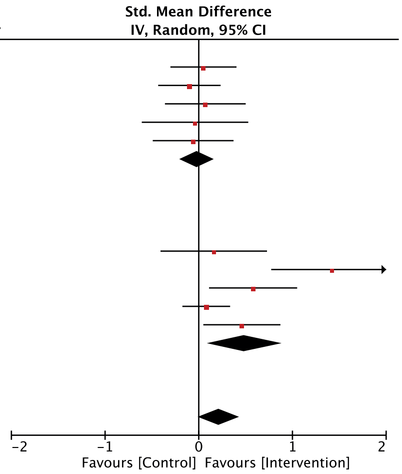


Fig 4. Forest plots for single-leg standing balance task. Task: Single-Leg Stand; Vision: Eyes open and closed; Surface: Stable and foam; Population: Healthy young; Older adults; Lower-limbs' injuries.

https://doi.org/10.1371/journal.pone.0174522.g004

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 Wearable Garments						
Hijmans et al. 2009	−0.76	0.22	27	27	5.2%	−0.76 [−1.19, −0.33]
Woo et al. 2014	−0.03	0.39	8	8	3.4%	−0.03 [−0.79, 0.73]
Genthon et al. 2010	0.14	0.13	53	53	6.1%	0.14 [−0.11, 0.39]
Kunzler et al. 2013	0.33	0.24	18	18	4.9%	0.33 [−0.14, 0.80]
Vuillerme & Pinault 2007	0.8	0.42	10	10	3.1%	0.80 [−0.02, 1.62]
Subtotal (95% CI)			**116**	**116**	**22.7%**	**0.05 [−0.42, 0.52]**
Heterogeneity: Tau² = 0.21; Chi² = 18.55, df = 4 (P = 0.0010); I² = 78%						
Test for overall effect: Z = 0.21 (P = 0.83)						
1.2.2 Textured Materials						
Corbin et al. 2007	−0.15	0.17	33	33	5.7%	−0.15 [−0.48, 0.18]
Hatton et al. 2012	−0.11	0.14	50	50	6.0%	−0.11 [−0.38, 0.16]
Hatton et al. 2011	−0.06	0.18	30	30	5.6%	−0.06 [−0.41, 0.29]
Hatton et al. 2009	0.01	0.2	24	24	5.4%	0.01 [−0.38, 0.40]
Palluel et al. 2009	0.1	0.16	36	36	5.8%	0.10 [−0.21, 0.41]
Palluel et al. 2008	0.1	0.23	19	19	5.0%	0.10 [−0.35, 0.55]
Qiu et al. 2013	0.46	0.16	40	40	5.8%	0.46 [0.15, 0.77]
Perry et al. 2008	0.7	0.17	20	20	5.7%	0.70 [0.37, 1.03]
Qiu et al. 2012	0.93	0.31	17	17	4.1%	0.93 [0.32, 1.54]
Menz et al. 2006	1.21	0.25	30	30	4.8%	1.21 [0.72, 1.70]
Subtotal (95% CI)			**299**	**299**	**54.1%**	**0.29 [0.03, 0.55]**
Heterogeneity: Tau² = 0.14; Chi² = 45.79, df = 9 (P < 0.00001); I² = 80%						
Test for overall effect: Z = 2.16 (P = 0.03)						
1.2.3 Stochastic Resonance						
Amiridis et al. 2005	0.13	0.21	11	10	5.3%	0.13 [−0.28, 0.54]
Ross et al 2013	0.37	0.21	12	12	5.3%	0.37 [−0.04, 0.78]
Magalhaes & Kohn 2011	0.56	0.35	11	11	3.7%	0.56 [−0.13, 1.25]
Kimura & Kouzaki 2013	0.58	0.33	12	12	3.9%	0.58 [−0.07, 1.23]
Dickstein et al. 2005	1.16	0.24	30	30	4.9%	1.16 [0.69, 1.63]
Subtotal (95% CI)			**76**	**75**	**23.2%**	**0.55 [0.17, 0.93]**
Heterogeneity: Tau² = 0.12; Chi² = 11.12, df = 4 (P = 0.03); I² = 64%						
Test for overall effect: Z = 2.84 (P = 0.004)						
Total (95% CI)			**491**	**490**	**100.0%**	**0.29 [0.10, 0.49]**
Heterogeneity: Tau² = 0.15; Chi² = 86.71, df = 19 (P < 0.00001); I² = 78%						
Test for overall effect: Z = 2.91 (P = 0.004)						
Test for subgroup differences: Chi² = 2.72, df = 2 (P = 0.26), I² = 26.5%						

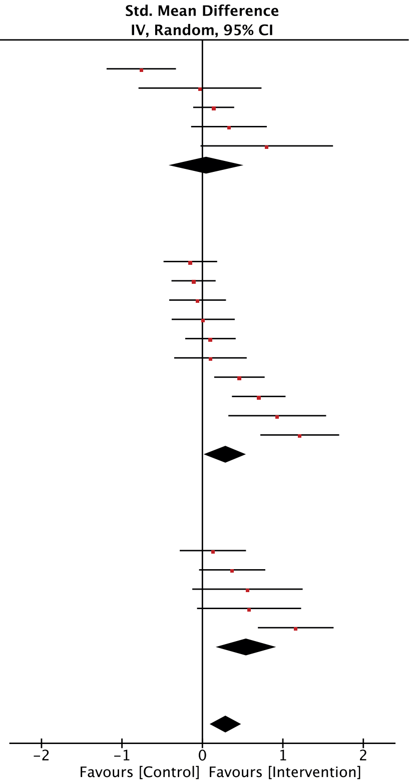


Fig 5. Forest plots for double-limbs standing balance task. Task: Double-limbs standing; Vision: Eyes open and closed; Surface: Stable and foam; Population: Healthy young; Older adults; Lower-limbs' injuries.

https://doi.org/10.1371/journal.pone.0174522.g005

small effect size. In comparison, the SRSS had a moderate effect size (SMD = 0.41). The overall application of both WGSS and SRSS during SLS had beneficial effects on postural regulation during performance of a SLS task on stable surfaces with eyes open and closed condition (z = 1.92, p = 0.05).

For the DLS balancing task, a total of 20 studies (WGSS = 5; TMSS = 10; SRSS = 5) were included for analysis (Fig 5). The mean effect sizes of TMSS (SMD = 0.29) and SRSS (SMD = 0.55) showed low to moderate effects of implementation of lower-limb stimulation strategies on performance in the DLS balance task. In contrast, the WGSS (SMD = 0.05) barely showed any effects on postural regulation measurements during the DLS balance task. All three groups revealed significant levels of heterogeneity, suggesting that different population samples, vision and surface conditions, or experimental design-related factors influenced levels of variability across effect sizes. The findings showed beneficial effects when applying all three lower-limb stimulation strategies during performance in the DLS task on stable surfaces (z = 2.91, p = 0.004).

In summary, the SRSS is more effective intervention strategy compared to TMSS and WGSS under the SLS and DLS conditions.

Populations: Young and healthy, elderly individuals and lower-limb injuries individuals. A total of 16 studies (WGSS = 6; TMSS = 6; SRSS = 4) that involved young and healthy adults, were included in the analysis (Fig 6). Of the three lower-limb stimulation strategy groupings, only the SRSS demonstrated a moderate positive effect (SMD = 0.66, p = 0.003) on

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1.4.1 Wearable Garments							
Vuillerme & Pinault 2007	0.8	0.42	10	10	4.2%	0.80 [−0.02, 1.62]	2007
Papadapoulos et al. 2007	−0.18	0.17	33	33	8.1%	−0.18 [−0.51, 0.15]	2007
Hijmans et al. 2009	−0.29	0.27	15	15	6.4%	−0.29 [−0.82, 0.24]	2009
Hadadi et al. 2011	−0.07	0.22	20	20	7.2%	−0.07 [−0.50, 0.36]	2011
Kunzler et al. 2013	0.33	0.24	18	18	6.9%	0.33 [−0.14, 0.80]	2013
Wheat et al. 2014	−0.15	0.29	13	13	6.0%	−0.15 [−0.72, 0.42]	2014
Subtotal (95% CI)			**109**	**109**	**38.8%**	**−0.00 [−0.26, 0.25]**	
Heterogeneity: $Tau^2 = 0.04$; $Chi^2 = 8.07$, df = 5 (P = 0.15); $I^2 = 38\%$							
Test for overall effect: Z = 0.02 (P = 0.98)							
1.4.2 Textured Material							
Menz et al. 2006	1.36	0.54	10	10	3.0%	1.36 [0.30, 2.42]	2006
Corbin et al. 2007	−0.15	0.17	33	33	8.1%	−0.15 [−0.48, 0.18]	2007
Palluel et al. 2008	0.06	0.23	19	19	7.1%	0.06 [−0.39, 0.51]	2008
Palluel et al. 2009	0.59	0.27	17	17	6.4%	0.59 [0.06, 1.12]	2009
Hatton et al. 2009	0.01	0.2	24	24	7.6%	0.01 [−0.38, 0.40]	2009
Qiu et al. 2012	0.67	0.4	10	10	4.4%	0.67 [−0.11, 1.45]	2012
Subtotal (95% CI)			**113**	**113**	**36.6%**	**0.26 [−0.08, 0.60]**	
Heterogeneity: $Tau^2 = 0.10$; $Chi^2 = 13.08$, df = 5 (P = 0.02); $I^2 = 62\%$							
Test for overall effect: Z = 1.51 (P = 0.13)							
1.4.3 Stochastic Resonance							
Dickstein et al. 2005	1.17	0.24	30	30	6.9%	1.17 [0.70, 1.64]	2005
Magalhaes & Kohn 2011	0.57	0.35	11	11	5.1%	0.57 [−0.12, 1.26]	2011
Kimura & Kouzaki 2013	0.58	0.34	12	12	5.2%	0.58 [−0.09, 1.25]	2013
Ross et al 2013	0.29	0.21	24	24	7.4%	0.29 [−0.12, 0.70]	2013
Subtotal (95% CI)			**77**	**77**	**24.6%**	**0.66 [0.22, 1.09]**	
Heterogeneity: $Tau^2 = 0.12$; $Chi^2 = 7.73$, df = 3 (P = 0.05); $I^2 = 61\%$							
Test for overall effect: Z = 2.95 (P = 0.003)							
Total (95% CI)			**299**	**299**	**100.0%**	**0.27 [0.05, 0.49]**	
Heterogeneity: $Tau^2 = 0.13$; $Chi^2 = 45.93$, df = 15 (P < 0.0001); $I^2 = 67\%$							
Test for overall effect: Z = 2.40 (P = 0.02)							
Test for subgroup differences: $Chi^2 = 6.77$, df = 2 (P = 0.03), $I^2 = 70.5\%$							

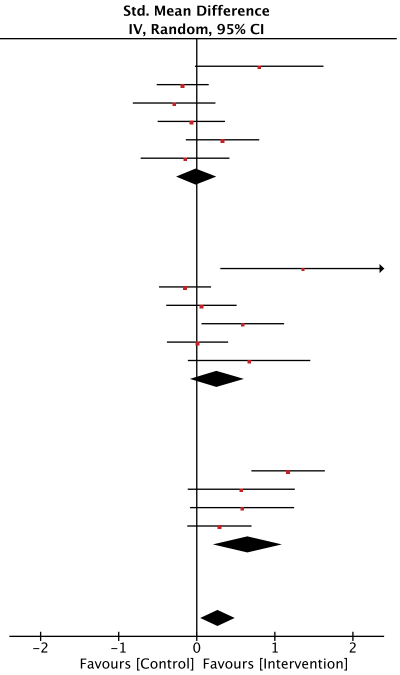


Fig 6. Forest plots for the young and healthy population. Population: Young and healthy; Vision: Eyes open and closed; Surface: Stable; Task: Single-leg and double-limbs standing tasks.

https://doi.org/10.1371/journal.pone.0174522.g006

postural regulation performance during static balance tasks—SLS and DLS on a stable surface with eyes open and closed. A forest plot showed that there was no effect demonstrated by WGSS (SMD = 0) and a low effect was observed in TMSS (SMD = 0.26). Both TMSS and SRSS showed moderate levels of heterogeneity: 62% & 67% respectively. There was an overall positive effect of applying SRSS observed in young adults on postural regulation during performance of static balance tasks on a stable surface with eyes open and closed (z = 2.95, p = 0.003).

For the elderly individuals, a forest plot (Fig 7) showed that there was a moderate negative effect of wearing compression garments (SMD = -0.68). The pooled effect size for TMSS and SRSS appeared low (SMD = 0.30 and 0.31 respectively). There was evidence of moderate heterogeneity for WGSS ($Tau^2 = 0.41$; df = 1; $I^2 = 69\%$), TMSS ($Tau^2 = 0.09$; df = 6; $I^2 = 61\%$) and SRSS ($Tau^2 = 0.10$; df = 2; $I^2 = 67\%$).

There were no differences across the lower-limb stimulation interventions on postural regulation during performance of static balance tasks on a stable surface with eyes open and eyes-closed (Fig 8). The pooled effect size values were low and moderate in WGSS (SMD = 0.20, z = 1.54, p = 0.12) and SRSS (SMD = 0.41, z = 1.75, p = 0.08) sub-groups, respectively.

In summary, the SRSS showed beneficial effects on postural regulation in all three populations. In contrast, the WGSS induced adverse effects in an elderly population.

Visions: Eyes open and—closed conditions. A significant negative pooled effect size observed in the WGSS sub-group (SMD = -0.21, z = 2.09, p = 0.04) during static balancing tasks performed by participants on a stable surface under the eyes open condition (Fig 9). In contrast, the SRSS subgroup had a significant positive pooled effect size (SMD = 0.49, z = 1.71, p = 0.008) under the same task constraints. There were significant levels of heterogeneity in both the TMSS ($Tau^2 = 0.19$; df = 8; $I^2 = 82\%$) and SRSS ($Tau^2 = 0.15$; df = 5; $I^2 = 74\%$)

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1.3.1 Wearable Garments							
Hijmans et al. 2009	−1.24	0.45	12	12	4.9%	−1.24 [−2.12, −0.36]	2009
Woo et al. 2014	−0.15	0.4	8	8	5.7%	−0.15 [−0.93, 0.63]	2014
Subtotal (95% CI)			**20**	**20**	**10.7%**	**−0.68 [−1.74, 0.39]**	
Heterogeneity: $Tau^2 = 0.41$; $Chi^2 = 3.28$, df = 1 (P = 0.07); $I^2 = 69\%$							
Test for overall effect: Z = 1.24 (P = 0.21)							
1.3.2 Textured Materials							
Menz et al. 2006	1.05	0.47	10	10	4.7%	1.05 [0.13, 1.97]	2006
Palluel et al. 2008	0.37	0.24	19	19	9.4%	0.37 [−0.10, 0.84]	2008
Palluel et al. 2009	0.71	0.27	19	19	8.6%	0.71 [0.18, 1.24]	2009
Hatton et al. 2011	−0.11	0.14	50	50	12.4%	−0.11 [−0.38, 0.16]	2011
Qiu et al. 2012	0.81	0.56	7	7	3.6%	0.81 [−0.29, 1.91]	2012
Hatton et al. 2012	−0.05	0.18	30	30	11.2%	−0.05 [−0.40, 0.30]	2012
Qiu et al. 2013	0.28	0.23	20	20	9.7%	0.28 [−0.17, 0.73]	2013
Subtotal (95% CI)			**155**	**155**	**59.7%**	**0.30 [0.00, 0.59]**	
Heterogeneity: $Tau^2 = 0.09$; $Chi^2 = 15.20$, df = 6 (P = 0.02); $I^2 = 61\%$							
Test for overall effect: Z = 1.97 (P = 0.05)							
1.3.3 Stochastic Resonance							
Gravelle et al. 2002	0.16	0.29	13	13	8.1%	0.16 [−0.41, 0.73]	2002
Amiridis et al. 2005	0.78	0.26	11	10	8.9%	0.78 [0.27, 1.29]	2005
Collins et al. 2012	0.07	0.13	52	52	12.7%	0.07 [−0.18, 0.32]	2012
Subtotal (95% CI)			**76**	**75**	**29.6%**	**0.31 [−0.13, 0.74]**	
Heterogeneity: $Tau^2 = 0.10$; $Chi^2 = 5.99$, df = 2 (P = 0.05); $I^2 = 67\%$							
Test for overall effect: Z = 1.38 (P = 0.17)							
Total (95% CI)			**251**	**250**	**100.0%**	**0.20 [−0.04, 0.44]**	
Heterogeneity: $Tau^2 = 0.10$; $Chi^2 = 31.51$, df = 11 (P = 0.0009); $I^2 = 65\%$							
Test for overall effect: Z = 1.66 (P = 0.10)							
Test for subgroup differences: $Chi^2 = 3.04$, df = 2 (P = 0.22), $I^2 = 34.3\%$							

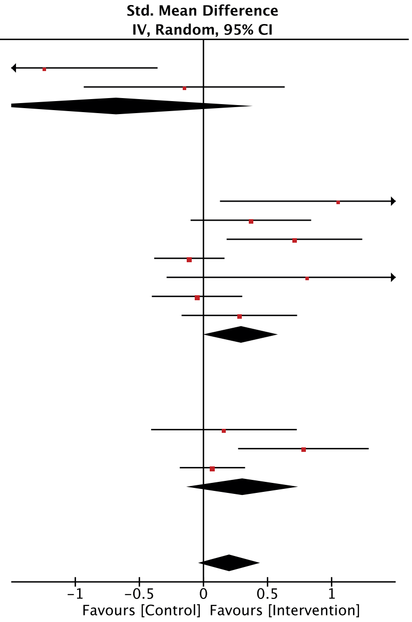


Fig 7. Forest plots for the older adults population. Population: Older adults; Vision: Eyes open and closed; Surface: Stable; Task: Single-leg and double-limbs standing tasks.

https://doi.org/10.1371/journal.pone.0174522.g007

subgroups. Conversely, homogeneity was observed in the pooled effect size of the WGSS subgroup.

A negative pooled effect size was observed in the WGSS sub-group (SMD = -0.16, z = 0.61, p = 0.54) for the static balance tasks performed by participants on a stable surface under the eyes closed condition (Fig 10). In contrast, the TMSS subgroup had a significant positive pooled effect size (SMD = 0.61, z = 2.97, p = 0.003) under the same task constraints. Of the 6 studies in the WGSS subgroup, only 2 studies demonstrated positive effects of interventions (Kunzler et al. [72]; Vuillerme & Pinsault [21]). There were significant heterogeneity levels in both the WGSS ($Tau^2 = 0.32$; df = 5; $I^2 = 81\%$) and TMSS ($Tau^2 = 0.20$; df = 5; $I^2 = 81\%$) subgroups.

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1.7.1 Wearable Garments							
Birmingham et al. 2001	0.02	0.18	30	30	19.6%	0.02 [−0.33, 0.37]	2001
Genthon et al. 2010	0.21	0.21	23	23	16.7%	0.21 [−0.20, 0.62]	2010
Hadadi et al. 2011	0.48	0.24	20	20	14.3%	0.48 [0.01, 0.95]	2011
Subtotal (95% CI)			**73**	**73**	**50.6%**	**0.20 [−0.05, 0.45]**	
Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 2.36$, df = 2 (P = 0.31); $I^2 = 15\%$							
Test for overall effect: Z = 1.54 (P = 0.12)							
1.7.2 Stochastic Resonance							
Ross 2007	0.58	0.34	12	12	8.8%	0.58 [−0.09, 1.25]	2007
Collins et al. 2012	0.08	0.13	52	52	25.6%	0.08 [−0.17, 0.33]	2012
Ross et al 2013	0.71	0.23	12	12	15.0%	0.71 [0.26, 1.16]	2013
Subtotal (95% CI)			**76**	**76**	**49.4%**	**0.41 [−0.05, 0.87]**	
Heterogeneity: $Tau^2 = 0.11$; $Chi^2 = 6.63$, df = 2 (P = 0.04); $I^2 = 70\%$							
Test for overall effect: Z = 1.75 (P = 0.08)							
Total (95% CI)			**149**	**149**	**100.0%**	**0.29 [0.06, 0.51]**	
Heterogeneity: $Tau^2 = 0.03$; $Chi^2 = 9.20$, df = 5 (P = 0.10); $I^2 = 46\%$							
Test for overall effect: Z = 2.49 (P = 0.01)							
Test for subgroup differences: $Chi^2 = 0.62$, df = 1 (P = 0.43), $I^2 = 0\%$							

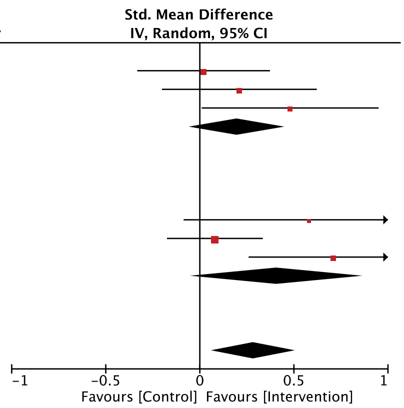


Fig 8. Forest plots for the lower-limbs' injuries population. Population: Lower-limbs' injuries; Vision: Eyes open and closed; Surface: Stable; Task: Single-leg and double-limbs standing tasks.

https://doi.org/10.1371/journal.pone.0174522.g008

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1.5.1 Wearable garments							
Papadapoulos et al. 2007	−0.16	0.17	33	33	5.7%	−0.16 [−0.49, 0.17]	2007
Hijmans et al. 2009	−0.47	0.2	27	27	5.4%	−0.47 [−0.86, −0.08]	2009
Hadadi et al. 2011	−0.07	0.22	20	20	5.2%	−0.07 [−0.50, 0.36]	2011
Wheat et al. 2014	−0.18	0.29	13	13	4.4%	−0.18 [−0.75, 0.39]	2014
Woo et al. 2014	0.02	0.39	8	8	3.4%	0.02 [−0.74, 0.78]	2014
Subtotal (95% CI)			**101**	**101**	**24.0%**	**−0.21 [−0.41, −0.01]**	
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 2.54$, df = 4 (P = 0.64); $I^2 = 0\%$							
Test for overall effect: Z = 2.09 (P = 0.04)							
1.5.2 Textured Materials							
Menz et al. 2006	1.165	0.31	20	20	4.2%	1.17 [0.56, 1.77]	2006
Corbin et al. 2007	−0.15	0.17	33	33	5.7%	−0.15 [−0.48, 0.18]	2007
Palluel et al. 2008	0.21	0.23	19	19	5.0%	0.21 [−0.24, 0.66]	2008
Hatton et al. 2009	0.01	0.2	24	24	5.4%	0.01 [−0.38, 0.40]	2009
Palluel et al. 2009	0.65	0.18	36	36	5.6%	0.65 [0.30, 1.00]	2009
Hatton et al. 2011	−0.34	0.14	50	50	6.0%	−0.34 [−0.61, −0.07]	2011
Qiu et al. 2012	0.87	0.3	17	17	4.3%	0.87 [0.28, 1.46]	2012
Hatton et al. 2012	−0.16	0.18	30	30	5.6%	−0.16 [−0.51, 0.19]	2012
Qiu et al. 2013	−0.35	0.23	20	20	5.0%	−0.35 [−0.80, 0.10]	2013
Subtotal (95% CI)			**249**	**249**	**46.8%**	**0.17 [−0.14, 0.49]**	
Heterogeneity: $Tau^2 = 0.19$; $Chi^2 = 45.57$, df = 8 (P < 0.00001); $I^2 = 82\%$							
Test for overall effect: Z = 1.06 (P = 0.29)							
1.5.3 Stochastic Resonance							
Gravelle et al. 2002	0.17	0.29	13	13	4.4%	0.17 [−0.40, 0.74]	2002
Dickstein et al. 2005	1.17	0.24	30	30	4.9%	1.17 [0.70, 1.64]	2005
Amiridis et al. 2005	0.78	0.26	10	11	4.7%	0.78 [0.27, 1.29]	2005
Magalhaes & Kohn 2011	0.57	0.35	11	11	3.8%	0.57 [−0.12, 1.26]	2011
Collins et al. 2012	0.08	0.13	52	52	6.1%	0.08 [−0.17, 0.33]	2012
Ross et al 2013	0.29	0.21	24	24	5.3%	0.29 [−0.12, 0.70]	2013
Subtotal (95% CI)			**140**	**141**	**29.2%**	**0.49 [0.13, 0.86]**	
Heterogeneity: $Tau^2 = 0.15$; $Chi^2 = 19.52$, df = 5 (P = 0.002); $I^2 = 74\%$							
Test for overall effect: Z = 2.64 (P = 0.008)							
Total (95% CI)			**490**	**491**	**100.0%**	**0.18 [−0.03, 0.38]**	
Heterogeneity: $Tau^2 = 0.16$; $Chi^2 = 87.50$, df = 19 (P < 0.00001); $I^2 = 78\%$							
Test for overall effect: Z = 1.71 (P = 0.09)							
Test for subgroup differences: $Chi^2 = 12.47$, df = 2 (P = 0.002), $I^2 = 84.0\%$							

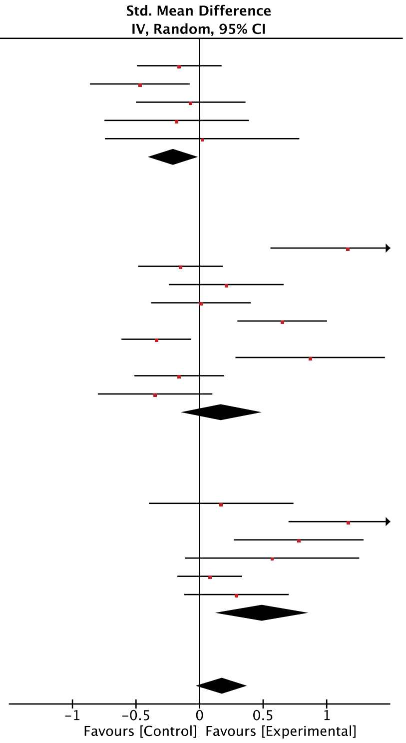


Fig 9. Forest plots for eyes open condition. Vision: Eyes open; Surface: Stable; Task: Single-leg and double-limbs standing tasks; Population: Healthy young; Older adults; Lower-limbs' injuries.

https://doi.org/10.1371/journal.pone.0174522.g009

Study or Subgroup	Std. Mean Difference	SE	Control Total	Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1.6.1 Wearable Garments							
Papadapoulos et al. 2007	−0.2	0.17	33	33	9.4%	−0.20 [−0.53, 0.13]	2007
Vuillerme & Pinault 2007	0.8	0.42	10	10	6.6%	0.80 [−0.02, 1.62]	2007
Hijmans et al. 2009	−1.3	0.28	27	27	8.2%	−1.30 [−1.85, −0.75]	2009
Kunzler et al. 2013	0.33	0.24	18	18	8.7%	0.33 [−0.14, 0.80]	2013
Wheat et al. 2014	−0.12	0.29	13	13	8.1%	−0.12 [−0.69, 0.45]	2014
Woo et al. 2014	−0.33	0.41	8	8	6.7%	−0.33 [−1.13, 0.47]	2014
Subtotal (95% CI)			**109**	**109**	**47.8%**	**−0.16 [−0.67, 0.35]**	
Heterogeneity: $Tau^2 = 0.32$; $Chi^2 = 26.14$, df = 5 (P < 0.0001); $I^2 = 81\%$							
Test for overall effect: Z = 0.61 (P = 0.54)							
1.6.2 Textured Materials							
Menz et al. 2006	1.24	0.32	20	20	7.8%	1.24 [0.61, 1.87]	2006
Corbin et al. 2007	1.01	0.22	33	33	8.9%	1.01 [0.58, 1.44]	2007
Hatton et al. 2011	0.11	0.14	50	50	9.7%	0.11 [−0.16, 0.38]	2011
Qiu et al. 2012	0.61	0.25	20	20	8.6%	0.61 [0.12, 1.10]	2012
Hatton et al. 2012	0.05	0.18	30	30	9.3%	0.05 [−0.30, 0.40]	2012
Qiu et al. 2013	0.92	0.31	17	17	7.9%	0.92 [0.31, 1.53]	2013
Subtotal (95% CI)			**170**	**170**	**52.2%**	**0.61 [0.21, 1.02]**	
Heterogeneity: $Tau^2 = 0.20$; $Chi^2 = 26.06$, df = 5 (P < 0.0001); $I^2 = 81\%$							
Test for overall effect: Z = 2.97 (P = 0.003)							
Total (95% CI)			**279**	**279**	**100.0%**	**0.25 [−0.10, 0.60]**	
Heterogeneity: $Tau^2 = 0.31$; $Chi^2 = 72.74$, df = 11 (P < 0.00001); $I^2 = 85\%$							
Test for overall effect: Z = 1.40 (P = 0.16)							
Test for subgroup differences: $Chi^2 = 5.40$, df = 1 (P = 0.02), $I^2 = 81.5\%$							

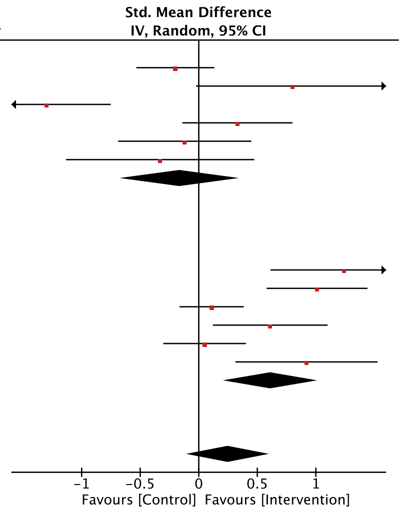


Fig 10. Forest plots for eyes- closed condition. Vision: Eyes- closed; Surface: Stable; Task: Single-leg and double-limbs standing tasks; Population: Healthy young; Older adults; Lower-limbs' injuries.

https://doi.org/10.1371/journal.pone.0174522.g010

In summary, WGSS did not have any beneficial effects for performance in the static standing task on a stable surface under both vision conditions. In contrast, SRSS & TMSS showed beneficial effects under the same conditions.

Discussion

The primary aim of this quantitative review was to investigate effectiveness of different lower-limb sensory stimulation strategies on postural regulation through systematic review and meta-analysis. Of additional interest was the comparison of effects with respect to three major subgroupings in the extant literature—WGSS, TMSS and SRSS in various populations (young and healthy; older adults; individuals with lower- limb injuries) and under different task and informational constraints (Unipedal; Bipedal; Eyes open; Eyes -closed). To the best of our knowledge, this is the first systematic review and meta-analysis comparing the effectiveness of various lower-limb stimulation strategies on postural regulation performance in different sub -populations.

Qualitative and quantitative analyses of SRSS studies showed significant positive effects of applying a SR strategy in young and healthy adults during static balance tasks (SLS & DLS) and in a vision condition. In contrast, a quantitative analysis of WGSS effectiveness showed no, or adverse, effects in older adults, young and healthy populations, during performance of static balance tasks (SLS & DLS), with eyes open and closed conditions. However, the qualitative analysis demonstrated some beneficial effects of using WGSS such as braces, tapes and compression sleeves. The quantitative and qualitative analyses suggested that TMSS studies revealed small and moderate positive effects of wearing textured materials on postural regulation during static and dynamic balance tasks.

Effects of Wearable Garment lower-limb Stimulation Strategies (WGSS)

Qualitative data suggested that wearable garments provide additional somatosensory information, inducing cutaneous pressure, probably by enhancing stimulation of plantar cutaneous receptors in the lower limbs [14,17,21,22,25,72], except in the elderly population. The quantitative outcomes of the review showed positive effects of wearable garments on postural control under static task constraints, revealing that enhanced performance was more prominent in people with lower-limb injuries [14,22,23,25,30,71] compared to a young, healthy people [19,20,23,24,26,52,71], and older adults [26,27]. These observations suggest that the disruptive effects of injury or illness on mechanoreceptors in an injured limb can be ameliorated by increasing stimulation of the cutaneous receptors through taping, braces and wearing compression garments. However, this was not the case for young, healthy adults, with few observed positive effects in quantitative analyses. This could be that “healthy postural control systems” may not benefit from the additional stimulation provided by wearable garments.

Only two studies, by Kunzler et al. [72] and Vuillerme and Pinsault [21] demonstrated a moderate to high positive effect size in applying the medical and athletic adhesive tapes in young and healthy adults during performance in the DLS balance tasks. In these studies, the tapes were placed on the anterior aspect of the ankle and along the Achilles tendon, unlike in other studies, where the entire ankles were wrapped/covered up by the braces, tapes or socks. Hence, it is possible that the pressure applied by the tapes in these two particular locations provided a more effective stimulant to the ankle joint receptors as well as the skin receptors in the lower limb. Further studies are needed to investigate location-specific effects of worn garments on motor task performance, to evaluate this possibility. It is plausible that the athletic taping could be used in sports that require high balance capacity such as ice dancing, Alpine skiing and gymnastics.

Studies by Hijmans et al. [26] and Woo et al. [27] are the only two studies to have examined the effect of compression garments (bandage and socks) on postural regulation in older adults. Hijmans et al. [26] found a main effect of compression, with balance significantly disturbed in the elderly aged 85.4 ± 4.6 years old. However, Woo et al. [27] concluded that both compression and commercial socks displayed similar functions in the regularization of anterior-posterior (AP) and medial-lateral (ML) motions, as seen under barefoot conditions for the elderly participants aged 70.9 ± 5.9 years old. The age groups of the participants for these two studies were different, which might explain the slight differences in the outcomes. Furthermore, the small sample size used in Woo et al. could have affected the reported outcomes. Nevertheless, these two studies left us with the question on whether wearing compression garments (e.g. socks and bandages) provide beneficial or deteriorating effects in influencing postural regulation in daily living activities in elderly populations remains unknown. Hence, more research is needed to investigate the effects of wearable garments on individuals of various ages in elderly populations.

Effects of Textured Materials lower-limb Stimulation Strategies (TMSS)

The qualitative review showed that double-limb standing balance measurements were most commonly used in studies of textured materials. Additionally, participants were almost always older adults. The quantitative review showed that textured insoles enhanced postural regulation performance in challenging conditions—during upright balance with eyes closed on a stable surface (SMD = 0.61), in older adults (SMD = 0.30).

The motivations behind these studies are rooted in ideas of deterioration of sensory system performance and the concept of sensory systems re-weighting their contributions to action regulation. Changes in cutaneous sensitivity and receptor morphology have been observed as people age, and have been associated with a reduction in neural activity, which increases the sensory and vibration threshold needed for accurate perception [27,59,79]. Studies included in this review reflect the role of textured insoles in enhancing the sensorimotor signals to provide plantar cutaneous afferent information in older adults during balance and postural regulation. These effects indirectly supported by evidence of textured insoles in improving postural regulation under DLS task constraints [7,54,57–59,64,74].

From the perspective of sensory re-weighting, individuals primarily rely on the somatosensory inputs when visual information is unavailable [80]. Presner-Domjan et al. [80] proposed that mechanical stimulations such as textured insoles could activate the plantar cutaneous receptors to compensate the loss of visual information. The idea of sensory re-weighting is supported by the quantitative analysis in this review, where high pooled effect size values (SMD = 0.61) were observed in the review of studies investigating effects of textured insoles on postural regulation during static balance tasks with eyes closed. This finding highlights an area requiring more research in the future, especially with regards to individuals with visual impairments and elderly people with eye problems (e.g. Cataract & Glaucoma). Furthermore, it might imply that such wearable technology might enhance somatosensory feedback to athletes during performance (e.g in gymnastics, skiing, football) and reduce the dependence on visual information during the competitive performance.

Of the 4 studies [7,55,56,59] that reported high positive effect sizes in favour of wearing added textured materials, the study by Menz et al. [56] is the only one that used velcro to stimulate the mechanoreceptors and skin receptors at either the ankle, calf, or knee. These findings prompt the question whether other sensory receptors in the lower limbs, besides the cutaneous receptors from the soles of the feet, could also be stimulated to enhance postural regulation system function. Furthermore, future research might consider altering task constraints, including difficulty levels of balance tasks (e.g., unstable with eyes open and -closed conditions), as noted in the studies by Qiu and colleagues' in 2012 [7] and 2013 [55].

It is also worth noting that the TMSS was the only lower-limb stimulation strategy not used to investigate the effects of textured materials on participants with lower-limb injuries. Previous studies have revealed beneficial effects seen in DLS task performance in other populations. It is plausible that people with lower-limb injuries could benefit from using the textured materials to help their balance and postural control. The findings of this systematic review and meta-analysis suggest that textured materials could be potentially used as a medium to ameliorate negative effects on the postural control system due to aging.

Effects of applying Stochastic Resonance as a lower-limb Stimulation Strategy (SRSS)

The qualitative analysis showed that 83.3% of the studies reported that imperceptible electrical stimulation (white noise, 0.01mA– 0.05mA) enhanced balance control, being associated with reduced postural sway during performance in static balance tasks. This stimulation strategy showed moderate- to high-pooled effect sizes in most of the populations and categories studied—young and older adults, healthy individuals, static balance tasks, and with vision available.

The current quantitative review focused on research studies with a common site of stimulation along the shank, and between the ankle and knee joints. Most of the electrodes were placed on the muscles, ligaments and bone (lateral and medial side of femoral condyles). It is postulated that muscle spindles and mechanoreceptors along the shank were sensitive to the stimulation by SR. Stimulation of these sites yielded beneficial effects on postural regulation in older adults, and in patients with lower limb injuries, as well as healthy young adults. A key difference in studies, noted from the review, concerns variations in the sites of stimulation, focusing on particular receptor(s). The majority of the studies in the WGSS grouping applied wearable garments at the ankle joint (targeting joint receptors). The soles of the feet (cutaneous receptors) were the most common stimulation sites used in TMSS studies. For the SRSS research, the site of stimulation was typically between the knee and the shank (targeting muscle spindles; mechanoreceptors). With the moderate to high effect sizes reported in the SRSS studies, investigators might wish to consider other sites of stimulation in future WGSS and TMSS studies.

The direct application of weak input signals (non-zero level of noise) enhanced the detection of sensorimotor signals, which were beneficial to motor task performance (e.g., balance) [44,45]. Our review article revealed that none of the previous studies measured the effects of SRSS on athletic performance and using athletes as the study sample (Table 1). Hence, this highlights another research areas for future studies to consider implementing this lower-limb stimulation strategy in sports contexts that require good balancing in performers, such as, competitive cycling, kicking a ball, skiing, snow and skateboarding and surfing.

Of three studies [39,40,42], the study by Kimura and Kouzaki [40] was the only one that reported the necessary information for effect size calculation in an eyes-closed condition. The moderate effect size (SMD = 0.58) prompts speculation that SRSS might also be effective under a condition where reliance on somatosensory system information is intensified by removal of available visual information. This suggests the possibility of using Stochastic Resonance to enhance somatosensory system signals and reduce the reliance on visual information for basic postural control. Future research could consider including an eyes-closed condition to measure the effects of applying SR on somatosensory system function and its effects on visually impaired populations.

Limitations and future research

A limitation of this review is that some outcomes included summary values extracted from graphs when values were not reported, reflecting estimations of the treatment effects. This review solely focused on research that had undergone rigorous, external peer review in international, scientific journals. The varied intervention periods in the 4 studies included in the meta-analysis might have had some impacts on the overall effects of the respective lower-limb stimulation strategies.

The findings of this review suggest three possible areas for future research. First, this review suggests that WGSS, TMSS and SRSS applications could be extended to the study of older adults, people with lower-limb injuries, as well as with elite and developing athletes, since many sports require attunement to information from the lower limbs for successful performance. Second, task performance difficulty levels need to be included in future analyses of experimental effects, such as the use of unstable surfaces in an eyes-closed condition and walking on uneven surfaces to measure the effectiveness of the lower-limb stimulation strategies. Third, at a later stage, there is a need to study effects of integrating two lower-limb stimulation strategies such as wearing textured and compression materials (or analysing the relative influence of different compression levels [clinical and non-clinical levels]) on the somatosensory system function in sports and clinical settings, particularly for developing athletes and in people with significant sensory function disorders.

Conclusion

A review of current evidence in published literature indicates that an SRSS has produced the most effective results in postural regulation, compared to implementing interventions with wearable garments and textured materials. An SRSS achieved moderate to high effect size in all the populations and task constraints studied—healthy young and older adults, single-leg and double-limbs standing balance tasks and eyes open condition. Regardless of these differences, the costs of the organising specific interventions also need to be considered. The review revealed that the WGSS was effective in studies of patients with lower-limb injuries, and TMSS was found to be beneficial in young and healthy population in a double-leg standing task. Future research can consider to investigate the effects of textured materials in populations with lower limb injuries during performance on a single- leg standing task. The usage of SRSS and WGSS could be extended out to neuropathy patients and elderly population respectively. Furthermore, researchers could use at least two of the currently used stimulation strategies in combination as an intervention treatment for people with significant sensory function disorders, or for the enhancement of skill and expertise in elite and developing athletes. The combination of two stimulation strategies might yield better results by enhancing the sensorimotor signals to the nervous system to support performance.

Supporting information

S1 PRISMA Checklist. PRISMA 2009 checklist.
(DOC)

S1 Table. Characteristic of included studies.
(DOCX)

Author Contributions

Conceptualization: MTW KD JL DO JYC TJ.

Data curation: MTW DO.

Formal analysis: MTW DO.

Investigation: MTW DO.

Methodology: MTW KD JL DO JYC TJ.

Project administration: MTW KD JL DO JYC TJ.

Resources: MTW DO.

Supervision: KD JL DO JYC TJ.

Validation: KD JL DO JYC TJ.

Visualization: MTW.

Writing – original draft: MTW.

Writing – review & editing: MTW KD JL DO JYC TJ.

References

1. Corbin DM, Hart JM, McKeon PO, Palmieri-Smith R, Ingersoll CD, Hertel J. The effect of textured insoles on postural control in double and single limb stance. Journal of Sport Rehabilitation. 2007; 16 (4):363–72. PMID: 18246902
2. Menant JC, Steele JR, Menz HB, Munro BJ, Lord SR. Optimizing footwear for older people at risk of falls. Journal of Rehabilitation Research & Development. 2008; 45(8):1167–82.
3. Hijmans JM, Geertzen JHB, Dijkstra PU, Postema K. A systematic review of the effects of shoes and other ankle or foot appliances on balance in older people and people with peripheral nervous system disorders. Gait & Posture. 2007; 25(2):316–23.
4. Hlavackova P, Vuillerme N. Do somatosensory conditions from the foot and ankle affect postural responses to plantar-flexor muscles fatigue during bipedal quiet stance? Gait & Posture. 2012; 36 (1):16–9.
5. Losa Iglesias ME, Becerro de Bengoa Vallejo R, Palacios Peña D. Impact of soft and hard insole density on postural stability in older adults. Geriatric Nursing. 2012; 33(4):264–71. https://doi.org/10.1016/j.gerinurse.2012.01.007 PMID: 22401984
6. Sungkarat S, Fisher BE, Kovindha A. Efficacy of an insole show wedge and augmented pressure sensor for gait training in individuals with stroke: a randomized controlled trial. Clinical Rehabilitation. 2011; 25:360–9. https://doi.org/10.1177/0269215510386125 PMID: 21148267
7. Qiu F, Cole MH, Davids KW, Hennig EM, Silburn PA, Netscher H, et al. Enhanced somatosensory information decreases postural sway in older people. Gait & posture. 2012; 35(4):630–5.
8. Kavounoudias A, Roll R, Roll J. The plantar sole is a 'dynamometric map' for human balance control. NeuroReport. 1998; 9(14):3247–52. PMID: 9831459
9. McKeon PO, Booi MJ, Branam B, Johnson DL, Mattacola CG. Lateral ankle ligament anesthesia significantly alters single limb postural control. Gait & Posture. 2010; 32(3):374–7.
10. Meyer P, Oddsson L, De Luca C. The role of plantar cutaneous sensation in unperturbed stance. Exp Brain Res. 2004; 156(4):505–12. https://doi.org/10.1007/s00221-003-1804-y PMID: 14968274
11. Stål F, Fransson PA, Magnusson M, Karlberg M. Effects of hypothermic anesthesia of the feet on vibration-induced body sway and adaptation. J Vestibular Res Equilib Orientat. 2003; 13(1):39–52.
12. Orth D, Davids K, Wheat J, Seifert L, Liukkonen J, Jaakkola T, et al. The role of textured material in supporting perceptual-motor functions. PLoS ONE. 2013; 8(4):e60349. https://doi.org/10.1371/journal.pone.0060349 PMID: 23565232
13. Raymond J, Nicholson LL, Hiller CE, Refshauge KM. The effect of ankle taping or bracing on proprioception in functional ankle instability: A systematic review and meta-analysis. J Sci Med Sport. 2012; 15 (5):386–92. https://doi.org/10.1016/j.jsams.2012.03.008 PMID: 22513304
14. Kuster MS, Grob K, Kuster M, Wood GA, Gächter A. The benefits of wearing a compression sleeve after ACL reconstruction. Medicine and Science in Sports and Exercise. 1999; 31(3):368–71. PMID: 10188739

15. Robbins S, Waked E, Rappel R. Ankle taping improves proprioception before and after exercise in young men. British Journal of Sports Medicine. 1995; 29(4):242–7. PMID: 8808537

16. Simoneau GG, Degner RM, Kramper CA, Kittleson KH. Changes in ankle joint proprioception resulting from strips of athletic tape applied over the skin. Journal of Athletic Training. 1997; 32(2):141–7. PMID: 16558444

17. Kraemer WJ, Bush JA, Newton RU, Duncan ND, Volek JS, Denegar CR, et al. Influence of a compression garment on repetitive power output production before and after different types of muscle fatigue. Sports Med. Training and Rehab. 1998; 8(2):163–84.

18. Robbins S, Waked E. Foot position awareness: The effect of footwear on instability, excessive impact, and ankle spraining. Crit Rev Phys Rehabil Med. 1997; 9(1):53–74.

19. Broglio SP, Monk A, Sopiarz K, Cooper ER. The influence of ankle support on postural control. Journal of Science and Medicine in Sport. 2009; 12(3):388–92. https://doi.org/10.1016/j.jsams.2007.12.010 PMID: 18550434

20. Ozer D, Senbursa G, Baltaci G, Hayran M. The effect on neuromuscular stability, performance, multi-joint coordination and proprioception of barefoot, taping or preventative bracing. The Foot. 2009; 19 (4):205–10. https://doi.org/10.1016/j.foot.2009.08.002 PMID: 20307478

21. Vuillerme N, Pinsault N. Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue. Exp Brain Res. 2007; 183 (3):323–7. https://doi.org/10.1007/s00221-007-1047-4 PMID: 17643234

22. Birmingham TB, Kramer JF, Kirkley A, Inglis JT, Spaulding SJ, Vandervoort AA. Knee bracing after ACL reconstruction: effects on postural control and proprioception. Medicine and Science in Sports and Exercise. 2001; 33(8):1253–8. PMID: 11474323

23. Hadadi M, Mazaheri M, Mousavi ME, Maroufi N, Bahramizadeh M, Fardipour S. Effects of soft and semi-rigid ankle orthoses on postural sway in people with and without functional ankle instability. J Sci Med Sport. 2011; 14(5):370–5. https://doi.org/10.1016/j.jsams.2010.12.004 PMID: 21237708

24. Papadopoulos ES, Nikolopoulos C, Badekas A, Vagenas G, Papadakis SA, Athanasopoulos S. The effect of different skin-ankle brace application pressures on quiet single-limb balance and electromyographic activation onset of lower limb muscles. BMC Musculoskeletal Disorders. 2007; 8(1):89.

25. Genthon N, Bouvat E, Banihachemi JJ, Bergeau J, Abdellaoui A, Rougier PR. Lateral ankle sprain alters postural control in bipedal stance: Part 2 sensorial and mechanical effects induced by wearing an ankle orthosis. Scan J Med Sci Sports. 2010; 20:255–61.

26. Hijmans JM, Zijlstra W, Geertzen JHB, Hof AL, Postema K. Foot and ankle compression improves joint position sense but not bipedal stance in older people. Gait & Posture. 2009; 29(2):322–5.

27. Woo MT, Davids K, Liukkonen J, Jaakkola T, Chow JY. Effects of textured compression socks on postural control in physically active elderly individuals. Procedia Engineering. 2014; 72:162–7.

28. Michael JS, Dogramaci SN, Steel KA, Graham KS. What is the effect of compression garments on a balance task in female athletes? Gait & Posture. 2014; 39(2):804–9.

29. Baier M, Hopf T. Ankle orthoses effect on single-limb standing balance in athletes with functional ankle instability. Archives of Physical Medicine and Rehabilitation. 1998; 79(8):939–44. PMID: 9710166

30. Palm H, Brattinger F, Stegmueller B, Achatz G, Riesner H, Friemert B. Effects of knee bracing on postural control after anterior cruciate ligament rupture. The Knee. 2012; 19(5):664–71. https://doi.org/10.1016/j.knee.2011.07.011 PMID: 21871811

31. You SH, Granata KP, Bunker LK. Effects of circumferential ankle pressure on ankle proprioception, stiffness, and postural stability: a preliminary investigation. The Journal of Orthopaedic and Sports Physical Therapy. 2004; 34(8):449–60. https://doi.org/10.2519/jospt.2004.34.8.449 PMID: 15373008

32. Horgan NF, Crehan F, Bartlett E, Keogan F, O'Grady AM, Moore AR, et al. The effects of usual footwear on balance amongst elderly women attending a day hospital. Age Ageing. 2009; 38(1):62–7. https://doi.org/10.1093/ageing/afn219 PMID: 19001558

33. Collins AT, Blackburn JT, Olcott CW, Miles J, Jordan J, Dirschl DR, et al. Stochastic resonance electrical stimulation to improve proprioception in knee osteoarthritis. The Knee. 2011; 18(5):317–22. https://doi.org/10.1016/j.knee.2010.07.001 PMID: 20655753

34. Ross SE. Noise-enhanced postural stability in subjects with functional ankle instability. British Journal of Sports Medicine. 2007; 41(10):656–9. https://doi.org/10.1136/bjsm.2006.032912 PMID: 17550917

35. Ross SE, Arnold BL, Blackburn JT, Brown CN, Guskiewicz KM. Enhanced balance associated with coordination training with stochastic resonance stimulation in subjects with functional ankle instability: an experimental trial. Journal of Neuroengineering and Rehabilitation. 2007; 4(1):47.

36. Ross S, Arnold B. Noise-enhanced dynamic single leg balance in subjects with functional ankle instability. Journal of Sport and Health Science. 2012; 1(2):102–6.

37. Amiridis I, Arabatzi F, Violaris P, Stavropoulos E, Hatzitaki V. Static balance improvement in elderly after dorsiflexors electrostimulation training. Eur J Appl Physiol. 2005; 94(4):424–33. https://doi.org/10.1007/s00421-005-1326-3 PMID: 15843959

38. Gravelle D, Laughton C, Dhruv N, Katdare K, Niemi J, Lipsitz L, et al. Noise-enhanced balance control in older adults. NeuroReport. 2002; 13(15):1853–6. PMID: 12395078

39. Dickstein R, Laufer Y, Katz M. TENS to the postertor aspect of the legs decreases postural sway during stance. Neuroscience Letters. 2005; 393:51–5. https://doi.org/10.1016/j.neulet.2005.09.039 PMID: 16207512

40. Kimura T, Kouzaki M. Electrical noise to a knee joint stabilizes quiet bipedal stance. Gait & Posture. 2013; 37(4):634–6.

41. Magalhães F, Kohn A. Imperceptible electrical noise attenuates isometric plantar flexion force fluctuations with correlated reductions in postural sway. Exp Brain Res. 2012; 217(2):175–86. https://doi.org/10.1007/s00221-011-2983-6 PMID: 22198530

42. Magalhães F, Kohn A. Effectiveness of electrical noise in reducing postural sway: a comparison between imperceptible stimulation applied to the anterior and to the posterior leg muscles. Eur J Appl Physiol. 2014; 114(6):1129–41. https://doi.org/10.1007/s00421-014-2846-5 PMID: 24563056

43. Sejdić E, Lipsitz LA. Necessity of noise in physiology and medicine. Computer Methods and Programs in Biomedicine. 2013; 111(2):459–70. https://doi.org/10.1016/j.cmpb.2013.03.014 PMID: 23639753

44. Cordo P, Ingils JT, Verschueren S, Collins JJ, Merfeld DM, Rosenblum S, et al. Noise in human muscle spindles [6]. Nature. 1996; 383(6603):769–70. https://doi.org/10.1038/383769a0 PMID: 8892999

45. Martínez L, Pérez T, Mirasso CR, Manjarrez E. Stochastic resonance in the motor system:effects of noise on the monosynaptic reflex pathway of the cat spinal cord. Journal of Neurophysiology. 2007; 97 (6):4007–16. https://doi.org/10.1152/jn.01164.2006 PMID: 17428901

46. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS medicine. 2009; 6(7):e1000097. https://doi.org/10.1371/journal.pmed.1000097 PMID: 19621072

47. Higgins J, Altman DG editors. The Cochrane Collaboration. London, UK: John Wiley & Sons, Ltd.; 2008.

48. Lin D, Seol H, Nussbaum MA, Madigan ML. Reliability of COP-based postural sway measures and age-related differences. Gait & Posture. 2008; 28(2):337–42.

49. Ruhe A, Fejer R, Walker B. The test—retest reliability of centre of pressure measures in bipedal static task conditions—A systematic review of the literature. Gait & Posture. 2010; 32(4):436–45.

50. Morris S, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and indepedent-groups designs. Psychological Methods. 2002; 7(1):105–25. PMID: 11928886

51. Borenstein M, Hedges L, Higgins J, Rothstein H. Introduction to Meta-Analysis. United Kingdom: John Wiley & Sons, Ltd; 2009.

52. Wheat JS, Haddad JM, Fedirchuk K, Davids K. Effects of textured socks on balance control during single-leg standing in healthy adults. Procedia Engineering. 2014; 72:120–5.

53. Hatton AL, Dixon J, Martin D, Rome K. The effect of textured surfaces on postural stability and lower limb muscle activity. J Electromyogr Kinesiology. 2009; 19(5):957–64.

54. Hatton AL, Dixon J, Rome K, Martin D. Standing on textured surfaces: Effects on standing balance in healthy older adults. Age Ageing. 2011; 40(3):363–8. https://doi.org/10.1093/ageing/afr026 PMID: 21450692

55. Qiu F, Cole MH, Davids KW, Hennig EM, Silburn PA, Netscher H, et al. Effects of textured insoles on balance in people with Parkinson's disease. PLoS ONE. 2013; 8(12):11–21.

56. Menz HB, Lord SR, Fitzpatrick RC. A tactile stimulus applied to the leg improves postural stability in young, old and neuropathic subjects. Neurosci Lett. 2006; 406(1–2):23–6. https://doi.org/10.1016/j.neulet.2006.07.014 PMID: 16904264

57. Palluel E, Nougier V, Olivier I. Do spike insoles enhance postural stability and plantar-surface cutaneous sensitivity in the elderly? AGE. 2008; 30(1):53–61. https://doi.org/10.1007/s11357-008-9047-2 PMID: 19424873

58. Palluel E, Olivier I, Nougier V. The lasting effects of spike insoles on postural control in the elderly. Behav Neurosci. 2009; 123(5):1141–7. https://doi.org/10.1037/a0017115 PMID: 19824780

59. Perry SD, Radtke A, McIlroy WE, Fernie GR, Maki BE. Efficacy and effectiveness of a balance-enhancing insole. The Journals of Gerontology. Series A, Biological sciences and medical sciences. 2008; 63 (6):595–602. PMID: 18559634

60. Wilson ML, Rome K, Hodgson D, Ball P. Effect of textured foot orthotics on static and dynamic postural stability in middle-aged females. Gait & Posture. 2008; 27(1):36–42.

61. Ross S, Guskiewicz K. Effect of coordination training with and without stochastic resonance stimulation on dynamic postural stability of subjects with functional ankle instability and subjects with stable ankles. Clinical Journal of Sport Medicine. 2006; 16(4):323–8. PMID: 16858216

62. Qu X. Impacts of different types of insoles on postural stability in older adults. Appl Ergon. 2015; 46 (PA):38–43.

63. Higgins JPT, Green S editors. Cochrane handbook for systematic reviews of interventions. 2011; http://www.cochrane-handbook.org/.

64. Hatton AL, Dixon J, Rome K, Newton JL, Martin DJ. Altering gait by way of stimulation of the plantar surface of the foot: the immediate effect of wearing textured insoles in older fallers. J Foot Ankle Res. 2012; 5(1):11.

65. Gribble PA, Taylor BL, Shinohara J. Bracing does not improve dynamic stability in chronic ankle instability subjects. Physical Therapy in Sport. 2010; 11(1):3–7. https://doi.org/10.1016/j.ptsp.2009.11.003 PMID: 20129116

66. Sperlich B, Born D, Swarén M, Kilian Y, Geesmann B, Kohl-Bareis M, et al. Is leg compression beneficial for alpine skiers? BMC Sports Science, Medicine and Rehabilitation. 2013; 5(1):18. https://doi.org/10.1186/2052-1847-5-18 PMID: 24004479

67. Cavanaugh M, Quigley P, Hodgson D, Reid J, Behm D. Kinesiology tape or compression sleeve applied to the thigh does not improve balance or muscle activation before or following fatigue. Journal of Strength and Conditioning Research. 2016; 30(7):1992–2000. https://doi.org/10.1519/JSC.0000000000001297 PMID: 26705066

68. Kelleher KJ, Spence WD, Solomonidis S, Apatsidis D. The effect of textured insoles on gait patterns of people with multiple sclerosis. Gait & Posture. 2010; 32:67–71.

69. Ma CC, Lee Y, Chen B, Aruin AS. Immediate and short-term effects of wearing a single textured insole on symmetry of stance and gait in healthy adults. Gait & Posture. 2016; 49:190–5.

70. Stern KA, Gottschall JS. Altering footwear type influences gait during level walking and downhill transitions. J Appl Biomech. 2012; 28(5):481–90. PMID: 23193066

71. Hadadi M, Mousavi ME, Fardipour S, Vameghi R, Mazaheri M. Effect of soft and semirigid ankle orthoses on Star Excursion Balance Test performance in patients with functional ankle instability. J Sci Med Sport. 2014; 17(4):430–3. https://doi.org/10.1016/j.jsams.2013.05.017 PMID: 23810776

72. Kunzler MR, Lopes LM, Ueda LS, de Britto MA, Carpes FP. Does skin stimulation compensate impairments in postural control after ankle plantar flexors fatigue? Gait & Posture. 2013; 37(4):611–4.

73. Aruin AS, Kanekar N. Effect of a textured insole on balance and gait symmetry. Exp Brain Res. 2013; 231(2):201–8. https://doi.org/10.1007/s00221-013-3685-z PMID: 23979014

74. Maki BE, Perry SD, Norrie RG, Mcllroy WE. Effect of facilitation of sensation from plantar foor-surface boundaries on postural stabilization in young and older adults. Journal of Gerontology. 1999; 54A (6):281–7.

75. Collings R, Paton J, Chockalingam N, Gorst T, Marsden J. Effects of the site and extent of plantar cutaneous stimulation on dynamic balance and muscle activity while walking. Foot. 2015; 25(3):159–63.

76. Jenkins ME, Almeida QJ, Spaulding SJ, van Oostveen RB, Holmes JD, Johnson AM, et al. Plantar cutaneous sensory stimulation improved single-limb support time, and EMG activation patterns among individuals with Parkinson's disease. Parkinsonism and Related Disorders. 2009:697–702. https://doi.org/10.1016/j.parkreldis.2009.04.004 PMID: 19467910

77. Ross SE, Linens SW, Wright CJ, Arnold BL. Customized noise-stimulation intensity for bipedal stability and unipedal balance deficits associated with functional ankle instability. Journal of Athletic Training. 2013; 48(4):463–70. https://doi.org/10.4085/1062-6050-48.3.12 PMID: 23724774

78. Lajoie Y, Gallagher SP. Predicting falls within the elderly community: comparison of postural sway, reaction time, the Berg balance scale and the Activities-specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. Archives of Gerontology and Geriatrics. 2004; 38(1):11–26. PMID: 14599700

79. Rose DJ. Fallproof!: a comprehensive balance and mobility training program. 2nd ed. Champaign IL: Human Kinetics; 2010.

80. Preszner-Domjan A, Nagy E, Sziver E, Feher-Kiss A, Horvath G, Kranicz J. When does mechanical plantar stimulation promote sensory re-weighing: Standing on a firm or compliant surface? Eur J Appl Physiol. 2012; 112(8):2979–87. https://doi.org/10.1007/s00421-011-2277-5 PMID: 22170016

II

FALLS, COGNITIVE FUNCTION, AND BALANCE PROFILES OF SINGAPORE COMMUNITY-DWELLING ELDERLY INDIVIDUALS: KEY RISK FACTORS

by

Woo, M. T., Davids, K., Liukkonen, J., Chow, J. Y.,
& Jaakkola, T. 2017

Geriatric Orthopaedic Surgery & Rehabilitation, 8(4), 256-262

https://doi.org/10.1177/2151458517745989

Article

Geriatric Orthopaedic Surgery & Rehabilitation
2017, Vol. 8(4) 256-262
© The Author(s) 2017
Reprints and permission:
sagepub.com/journalsPermissions.nav
DOI: 10.1177/2151458517745989
journals.sagepub.com/home/gos
SAGE

Falls, Cognitive Function, and Balance Profiles of Singapore Community-Dwelling Elderly Individuals: Key Risk Factors

Mei Teng Woo, Msc[1,2], Keith Davids, PhD[3], Jarmo Liukkonen, PhD[1], Jia Yi Chow, PhD[4], and Timo Jaakkola, PhD[1]

Abstract

Objective: This study compared occurrence of falls, cognitive function, and balance profiles across participants in elderly age categories, investigating associations between the 3 aspects in a sample of Singapore's elderly population. **Method:** Community-dwelling elderly individuals (N = 385) were randomly recruited and grouped into "young-old (65-74 years)," "medium-old (75-84 years)," and "oldest-old (above 85 years)" groups. The Fallproof Health and Activity questionnaire, adapted Mini-Mental State Examination (MMSE), and Berg Balance Scale (BBS) tests were used to survey information related to falls, cognition, and balance profiles. **Results:** Findings revealed significant differences in MMSE and BBS scores across the age groups. Participants with mild cognitive impairment (odds ratio [OR] = 1.87, 95% confidence interval [CI] = 1.08-3.25) and BBS score ≤40 (OR = 0.25, 95% CI = 0.14-0.46) were at the highest risk of falling. **Conclusion:** Community-dwelling elderly individuals with subtle cognitive impairment and BBS scores ≤40 displayed an increased risk of falling.

Keywords

elderly individuals, cognitive functioning, Berg Balance Scale, falls, MMSE

Submitted May 09, 2017. Revised September 16, 2017. Accepted October 26, 2017.

Introduction

Falling is a common public health problem for elderly individuals and is the fifth leading cause of death.[1,2] In Singapore, Chan and colleagues[3] found that 17.2% (N = 3000) of the elderly population experienced at least 1 fall a year. In 2009, the National University Hospital of Singapore reported that 85.3% of the elderly peoples' injuries that required help in the emergency department were due to falls.[4] Based on data from the Singapore National Trauma Registry, a recent study by Wong et al[5] found that more than 88% of elderly patients experienced falls between 2011 and 2013.

Cognitive functioning and balance abilities are 2 primary factors for falls.[6] To date, fall risk is closely related to severe cognitive impairment in elderly individuals who have dementia.[7] Often, falls management programs and guidelines are directed toward this group of elderly individuals.[7] However, it is possible that a subtle decline in cognitive functioning can contribute to postural instability[8] and increase the risk of falling.[9] The association between cognitive functioning and fall risk arises from the perspective of aging of the frontal cortex and the changes in white matter of the brain.[10-12] Subtle changes in cognitive functioning might lead to poor judgments and decision-making[13]; declines in executive function, attention, and processing speed[10,12]; and decrements in verbal reasoning and ability,[14] which could increase the risk of falling. This may become a particular problem when individuals with mild cognitive impairments may need to engage in dual tasking in everyday life (eg, when talking and climbing up a staircase or navigating an uneven surface on the road). Hence, the early detection of subtle cognitive impairments might help health

[1] Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland
[2] School of Sports, Health, and Leisure, Republic Polytechnic, Singapore
[3] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, United Kingdom
[4] Physical Education and Sports Science, National Institute of Education, Nanyang Technological University, Singapore

Corresponding Author:
Mei Teng Woo, School of Sports, Health, and Leisure, Republic Polytechnic, 9 Woodlands Avenue 9, Singapore 738964, Singapore.
Email: woo_mei_teng@rp.edu.sg

practitioners to better identify the degree of fall risk in community-dwelling elderly people.

On the other hand, balance impairment has been recognized as a major risk factor for falls in older people.[15,16] Research has demonstrated that lack of ability in balance control is associated with a higher risk of falling.[15,17,18] Deterioration in biological systems, such as declines in sensory system capacity, neurological functioning, and motor functions and increased reaction time in elderly populations, causes delays in stabilization of control systems, which could contribute to postural instability and falls.[19,20] It is also possible that cognition plays a key role in balance regulation in older adults, where the motor and sensory systems are integrated through higher order neurological processes.[8] Tangen and colleagues found that a decline in balance ability was associated with increasing severity of cognitive impairment.[21] Therefore, we sought to understand whether a similar linear association existed between cognitive function and balance abilities in a community-dwelling elderly population in an Asian community.

Cognitive functioning and balance abilities have been commonly tested by researchers to predict fall risk, especially in elderly people with severe cognitive impairment and neurological conditions such as multiple sclerosis and Alzheimer disease.[8,11,22,23] However, studies examining falls, cognitive function, and balance profiles of a community-dwelling elderly population and the association between these 3 aspects are scarce in Asia. This study sought to contribute to the literature by researching the relations between these 3 phenomena in different categories of elderly people in an Asian population. The primary aims of this study were to (1) compare occurrence of falls, cognition, and balance profiles across people in elderly age categories; (2) investigate the association between the 3 aspects; and (3) provide suggestions for the development of simple screening interventions in a sample of Singapore's elderly population.

Method

Participants

A total of 385 community-dwelling, elderly individuals (65 years and above) were recruited randomly from Singaporean communities. Recruitment e-mails were sent to senior activity centers, government organizations, and social development groups across Singapore. Based on Singapore's Department of Statistics (2007), the age groups of the elderly people were identified as "young-old (65-74 years)," "medium-old (75-84 years)," and "oldest-old (above 85 years)" in this study.[24] Ethics approval was sought from the ethics committee of the Nanyang Technological University, Singapore. Informed consent was obtained from all participants, and procedures used in the study were in accordance with ethical guidelines. Specific inclusion criteria were ability to walk independently, either with or without any assistive device, and freedom from diagnosed cognitive dysfunctions (eg, dementia and Alzheimer disease). Exclusion criteria were history of severe rheumatic arthritis, neuropathy injury, recent stroke events (<18 months), brain injuries, and diagnosed cognitive dysfunctions.

Table 1. Berg Balance Scale Items.

Item	Description
1	Sitting to standing
2	Standing unsupported
3	Sitting unsupported
4	Standing to sitting
5	Transfers
6	Standing with eyes closed
7	Standing with feet together
8	Reaching forward with an outstretched arm
9	Object pick up from floor
10	Turning to look behind (twisting)
11	Turning 360°
12	Placing alternate foot on stool (stepping)
13	Tandem standing
14	One leg standing

Procedure

A complete testing session included a 20-minute semi-structured interview based on material from the Fallproof Health and Activity questionnaire,[18] Mini-Mental State Examination (MMSE) adapted from Folstein et al,[25] and Berg Balance Scale (BBS) test.[15] For the interviews, each participant was required to complete the questionnaire (Fallproof Health and Activity) either via an informal interview with the researcher or independently. The MMSE test was used to assess cognitive functions as the test is used to quantitatively assess the severity of cognitive impairment and documents cognitive changes occurring over time.[26] There were 3 categories of cognitive function levels—no cognitive impairment (>24), mild cognitive impairment (18-23), and severe cognitive impairment (<17).[26] The MMSE had a high test–retest level of reliability ($r = .83$) in assessing cognitive functioning in elderly populations.[25] An updated comprehensive review found that the reliability coefficient ranged between 0.64 and 0.97 for the sample populations aged between 58 and 86 years old.[26] The cutoff score of <24 showed sensitivity levels of 0.63 and a specificity of 0.96 in predicting the risk of cognitive impairment.[27] The BBS is a commonly used subjective assessment tool used globally in predicting falls among elderly people.[15,28] The BBS had high reliability ($r \geq .75$) in assessing balance abilities in elderly people.[15,28,29] The sensitivity and specificity of the BBS test were high in predicting the risk of falls in elderly persons.[20,30,31] Lastly, the BBS was administered, a scale consisting of 14 subtests, with each subtest scores ranging from 0 to 4, performed in a standard order (Table 1) to measure functional abilities and balance. The maximum score for this assessment is 56. The categories were low risk of falling (41-56) and increased risk of falling ($\leq$40).[31]

All interviews were conducted in accordance with the preferred language (eg, English, Mandarin, Malay, and local

Table 2. Demographics of the Participants.[a]

Characteristics	Young-Old (n = 212)	Medium-Old (n = 146)	Oldest-Old (n =27)	*P* Value
Age, mean (SD)	69.63 (2.97)	79.14 (2.95)	88.22 (2.91)	<.001
Height, m, mean (SD)	1.56 (0.08)	1.53 (0.08)	1.51 (0.07)	>.05
Weight, kg, mean (SD)	60.56 (11.05)	54.10 (9.82)	51.44 (9.58)	<.001
BMI, mean (SD)	25.17 (4.98)	23.21 (3.94)	22.45 (3.65)	<.05
MMSE scores, mean (SD)	22.51 (5.03)	21.18 (4.88)	17.93 (5.04)	<.001
BBS scores, mean (SD)	47.37 (7.82)	45.12 (7.72)	40.74 (6.97)	<.001
Amount of exercise (×days/week), mean (SD)	2.1 (2.7)	2.3 (2.7)	1.3 (2.2)	
Gender, n (%)				
Male	81 (38.2)	52 (35.6)	6 (22.2)	
Female	131 (61.8)	94 (64.4)	21 (77.8)	
Ethnicity, n (%)				
Chinese	132 (62.3)	112 (76.7)	25 (92.6)	
Malay	71 (33.5)	30 (20.5)	2 (7.4)	
Indian	4 (1.9)	0 (2.7)	0 (0)	
Others	5 (2.4)	4 (0)	0 (0)	
Medical conditions, n (%)				
Hypertension	136 (64.2)	83 (56.8)	17 (63)	
High cholesterol	102 (48.1)	73 (50)	12 (44.4)	
Diabetes	53 (25)	46 (31.4)	9 (33.3)	
Falls in the past 1 year, n (%)				
Yes	58 (27.4)	40 (27.4)	9 (33.3)	
No	154 (72.6)	106 (72.6)	18 (66.7)	
Assistive device used in walking, n (%)				
Yes	38 (17.9)	45 (30.8)	13 (48.1)	
No	174 (82.1)	101 (69.2)	25 (51.9)	
Education, n (%)				
≤6 years of education	147 (69.3)	134 (91.8)	25 (92.6)	
>6 years of education	65 (30.7)	12 (8.2)	2 (7.4)	
MMSE categories, n (%)				
No cognitive impairment (≥24 scores)	100 (47.2)	56 (38.4)	5 (18.5)	
Mild cognitive impairment (18-23 scores)	75 (35.4)	57 (39.0)	8 (29.6)	
Severe cognitive impairment (≤17 scores)	37 (17.5)	33 (22.6)	14 (51.9)	
BBS categories, n (%)				
Low fall risk (41-56 scores)	183 (86.3)	122 (83.6)	15 (55.6)	
Increased fall risk (≤40 scores)	29 (13.7)	24 (16.4)	12 (44.4)	

[a]N = 385.
Abbreviations: BBS, Berg Balance Scale; BMI, body mass index; MMSE, Mini-Mental State Examination; SD, standard deviation.

dialects) used by the elderly participants to ensure adequate understanding of questions and provision of accurate information. Researchers were competent in speaking each participant's preferred language. All testing sessions were voice recorded for further analysis and clarification. Two short breaks were provided for participants during the testing session: after the questionnaire interview and after the MMSE test.

Statistical Analysis

The Statistical Program for Social Sciences software version 22.0 was used for statistical analysis. For all outcome measures, between-group differences in mean change were analyzed by using a nonparametric test—Friedman test. Post hoc testing was performed using a Wilcoxon signed-rank test when the Friedman analysis of variance resulted in a statistically significant outcome (α value set at $P < .05$). Results were reported as means $\pm$ standard deviation (SD) for the descriptive data and z score (z) and Wilcoxon (W) for the Mann-Whitney (U) test. Binary logistic regression was used to estimate the odds ratios of risk factors associated with falls. Spearman correlation test was used to identify the correlations between MMSE and BBS scores in the 3 age categories.

Results

Table 2 shows the sociodemographic characteristics, cognitive assessment levels, the risk of falls, and medical conditions in young-old, medium-old, and oldest-old groups. The ethnicity distribution of the 385 participants was as follows: 69.9% were Chinese, 26.2% were Malay, 3.1% were Indian, and 0.8% were others. The distribution was close to the national ethnicity distribution in Singapore: Chinese (74.3%), Malays (13.3%), Indians (9.1%), and others (3.2%).[32] Regarding gender distribution, there were 246 females and 139 males for this study; 83.7% (n = 206) of females and 71.9% (n = 100) of males had

Table 3. Gender Comparisons of MMSE and BBS Scores.

Overall Gender Comparisons			
	MMSE	BBS	
Male	23.4 ± 5.1	47.5 ± 7.9	
Female	22.0 ± 4.9[a]	45.2 ± 7.8[a]	
MMSE Score According to Age Groups			
	Young-Old	Medium-Old	Oldest-Old
Male	23.4 ± 5.1	22.4 ± 4.2	18.0 ± 6.8
Female	22.0 ± 4.9[a]	20.5 ± 5.1[a]	17.9 ± 4.6
BBS Score According to Age Groups			
	Young-Old	Medium-Old	Oldest-Old
Male	48.5 ± 8.1	46.3 ± 7.7	44.8 ± 3.8
Female	46.7 ± 7.6[a]	44.5 ± 7.7	39.6 ± 7.3

Abbreviations: BBS, Berg Balance Scale; MMSE, Mini-Mental State Examination.
[a] Significant difference from male participants.

Table 4. Independent Risk Factors for Fall and Cognitive Impairment Levels.

Binary logistic regression: Odds Ratios (OR) and 95% Confidence Intervals (CIs) for Fall

Characteristics	*B* (SE)	OR	95% CI	*P* Value
MMSE categories				
No cognitive impairment (≥24 scores)		1	Reference	
Mild cognitive impairment (18-23 scores)	0.63 (0.28)	1.874	1.080-3.250	<.05
Severe cognitive impairment (≤17 scores)	0.32 (0.32)	1.376	0.730-2.59	
BBS categories				
Low fall risk (41-56 scores)		1	Reference	
Increased fall risk (≤40 scores)	−1.370 (0.306)	0.254	0.14-0.463	<.001

Abbreviations: BBS, Berg Balance Scale; MMSE, Mini-Mental State Examination; SE, standard error.

less than 6 years of education. Nonparametric testing revealed significant differences in weight, BMI, MMSE, and BBS scores across the 3 age groups ($P < .05$). The males displayed significantly higher scores on both MMSE ($U = 13\ 560.50$, $W = 43\ 941.5$, $Z = -3.379$, $P < .05$) and BBS tests ($U = 13\ 459.5$, $W = 43\ 840.5$, $Z = -3.473$, $P < .05$; Table 3). A higher percentage of fall incidents was observed in the oldest-old group compared to the other 2 groups. It was observed that the proportion of community-dwelling elderly individuals using an assistive device when walking increased with age.

Table 4 shows the risk factors for falls and cognitive impairment levels. Risk of falling was significantly higher in those who had mild cognitive impairment and with BBS scores at and below the cutoff of 40.

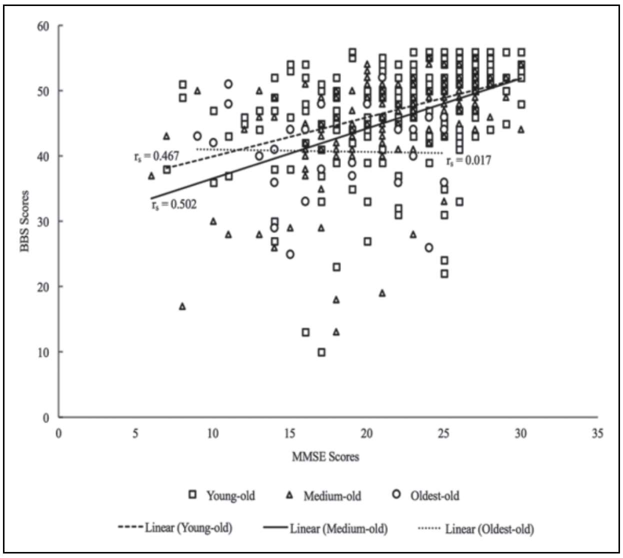


Figure 1. Spearman correlation between MMSE and BBS scores of the 3 age categories—young-old, medium-old, and oldest-old. BBS denotes Berg Balance Scale; MMSE, Mini-Mental State Examination.

Overall, a moderate Spearman ρ correlation value ($r = .485$, $P = .000$) was found between MMSE and BBS. A significant moderate relationship was also determined between MMSE and BBS in young-old ($r = .467$, $P = .000$) and medium-old ($r = .502$, $P = .000$) groups (Figure 1). However, no relationship was found between MMSE and BBS scores in the oldest-old group.

Discussion

The aims of this study were to (1) compare occurrence of falls, cognition, and balance (2 primary implicated factors) profiles across elderly age categories; (2) investigate associations between them; and (3) provide suggestions for the development of simple screening interventions in a sample of Singapore's elderly population. In this screening of Singapore community-dwelling participants, it was observed that elderly individuals had significant declines in cognitive functioning and balance abilities between young-old (65-74 years old) and oldest-old (>85 years old) groups. Mean MMSE scores showed that the level of cognitive function was classified as mild cognitive impairment, for both genders, but especially in females, in all 3 groups. The oldest-old group had a higher percentage of fall incidences, higher risk of cognitive impairment, and increased risk of falls, compared to the younger 2 groups. The risk factor analysis showed that mild cognitive impairment and balance scores ≤40 were associated with falls. Last, we found a moderate correlation between MMSE and BBS scores in the young-old and medium-old age groups.

The findings showed that both cognitive functions and balance abilities significantly declined as people aged. In line with the outcomes of other studies, the current finding also indicates that community-dwelling elderly individuals with mild cognitive impairment[9,13,33,34] and balance impairment[20,31,34] were most at risk of falling. From the aging perspective, deteriorating speed of cognitive function, a decline in attention and executive function (eg, slow response inhibitions and judgment errors), and declines in sensory systems, due to the aging of the frontal cortex, could be the biggest factors for an increased risk of falling.[7,10,18] Furthermore, cognition plays a vital role in the balance regulation in older adults.[8] The decline in cognitive function observed might explain the increased risk of falling in this sampled population.

The results of our study have shown that Singapore's community-dwelling elderly individuals display subtle declines in cognition (mild cognitive impairment), with functional performance below the average scores found in other studies, of similar age groups, conducted in the United States, Japan, Korea, Brazil, China, United Kingdom and Turkey.[35] It is plausible that the low education level of the majority of participants in the sampled groups contributed to the subtle decline in cognitive functioning, as education is one of the primary protective mechanisms for cognitive impairment.[34] This assumption on the role of education in cognitive impairment is supported by data of Seeman et al,[36] who found that highly educated groups were less likely to exhibit cognitive impairment in a group of elderly individuals, aged 70 to 79 years old. Albert[37] suggested that low levels of education relate to cognitive declines based on the fact that effects of education on the increment of synaptic density in the brain in the early stages of life could delay the appearance of cognitive declines in old age. Eggenberger et al[38] suggested that an intervention exercise that combined cognitive and motor training (eg, interactive cognitive motor video game dancing) improved cognitive function of older adults. Hence, clinicians and health practitioners could consider the alternative solutions/interventions exercises suggested by Eggenberger et al[38] to tackle health-related issues on falls, balance, and cognitive deterioration and impairment.

The current findings suggest that the results from the MMSE and BBS tools could be used to predict the risk of falling. The use of the MMSE test tool to predict falls has displayed mixed results.[8] Muir et al[8] suggested that MMSE scores at and below 26 were strongly associated with the high risk of severe fall-related injury. Mirelman et al[7] and Mitchell[39] concluded that the MMSE test tool was not strongly associated with fall risk among community-living older adults. In contrast, our results supported the findings of Gleason et al,[9] which suggested that a decrease in MMSE scores was associated with elevations in the rate of falls. We found that subtle cognitive deficits can increase the risk of falls. On the other hand, the BBS tool produced the highest sensitivity in predicting falls in independent functioning, community-dwelling elderly individuals.[30,31] However, Muir et al[16] found that the BBS tool, with the cutoff value at 45, failed to identify people at a high risk of falling (multiple falls). They suggested that the use of a scale cutoff point of 45, suggested by Berg et al,[15] was inadequate to predict future falls. Our study adopted a cutoff point of 40 and it seemed to have a predictive value for risk of falls.[30,31] Thus, it is suggested that the BBS test tool, with a cutoff point of 40, could be adopted by health practitioners as part of an initial simple screening assessment procedure for the community-dwelling elderly population in Singapore. Further analysis of correlations between MMSE and BBS test scores indicated a moderate relationship in young-old and medium-old groups. This finding suggests that a decline in cognitive ability might have led to a decrease in balance performance, suggesting that clinicians and health practitioners of Singapore could adopt the BBS test as a baseline screening tool to identify potential cognitive impairment in the young-old and medium-old groups.

One limitation of the study was the self-reporting of fall incidences, with a possibility of underreporting by the older participants. The major implication of this study is that health professionals could use the MMSE and BBS tests as predictors for falls in elderly individuals, aged below 85 years. Health professionals might need to explore ways to decelerate deterioration in cognitive function and develop strategies for fall prevention, especially in the oldest group. These strategies could include activities for elderly people to engage the brain and enhance nervous system function. These could include balance and mobility exercise training, use of problem-solving and perceptual awareness activities, cognitive and memory games, and discussion of health education and home safety guidelines. Among elderly individuals, we noted a moderate relationship found between cognitive decline and the risk of falls, and either test could be used as a simple screening tool to incorporate in a routine primary care assessment in Singapore, with further evaluations needed in other South East Asia (SEA) countries.

Conclusion

In conclusion, findings revealed that participants older than 85 years had the highest number of fall incidents, combined with mild impairments displayed in the cognitive and balance assessments. Balance ability and cognitive functioning levels were the biggest risk factors for falls. A significant moderate relationship was determined between MMSE and BBS tests in the young-old (65-74 years old) and medium-old (75-84 years old) groups. This relationship indicates that the MMSE and BBS tools could be incorporated into a routine primary care assessment in Singapore. Future studies could examine and evaluate the use of the MMSE and BBS tests in other SEA countries.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: National Institute of Education(NIE) Academic Research Fund, Singapore (AcRF) x [RI 8/13 CJY].

ORCID iD

Mei Teng Woo, Msc http://orcid.org/0000-0003-1289-9538

References

1. Kannus P, Parkkari J, Niemi S, Palvanen M. Fall-induced deaths among elderly people. *Am J Public Health*. 2005;95(3):422-424. doi:10.2105/AJPH.2004.047779.
2. Kannus P, Sievänen H, Palvanen M, Järvinen T, Parkkari J. Prevention of falls and consequent injuries in elderly people. *Lancet*. 2005;366(9500):1885-1893. doi:10.1016/S0140-6736(05)67604-0.
3. Chan KM, Pang WS, Ee CH, Ding YY, Choo P. Epidemiology of falls among the elderly community dwellers in Singapore. *Singapore Med J*. 1997;38(10):427-431.
4. Yeo YY, Lee SK, Lim CY, Quek LS, Ooi SB. A review of elderly injuries seen in a Singapore emergency department. *Singapore Med J*. 2009;50(3):278-283.
5. Wong TH, Nguyen HV, Chiu MT, et al. The low fall as a surrogate marker of frailty predicts long-term mortality in older trauma patients. *PLoS One*. 2015;10(9). doi:10.1371/journal.pone.0137127.
6. Whitney J, Close JCT, Lord SR, Jackson SH. Identification of high risk fallers among older people living in residential care facilities: a simple screen based on easily collectable measures. *Arch Gerontol Geriatr*. 2012;55(3):690-695. doi:10.1016/j.archger.2012.05.010.
7. Mirelman A, Herman T, Brozgol M, et al. Executive function and falls in older adults: new findings from a five-year prospective study link fall risk to cognition. *PLoS One*. 2012;7(6):e40297. doi:10.1371/journal.pone.0040297.
8. Muir SW, Gopaul K, Montero Odasso MM. The role of cognitive impairment in fall risk among older adults: a systematic review and meta-analysis. *Age Ageing*. 2012;41(3):299-308. doi:10.1093/ageing/afs012.
9. Gleason CE, Gangnon RE, Fischer BL, Mahoney JE. Increased risk for falling associated with subtle cognitive impairment: secondary analysis of a randomized clinical trial. *Dement Geriatr Cogn Disord*. 2009;27(6):557-563. doi:10.1159/000228257.
10. Gunning-Dixon FM, Raz N. The cognitive correlates of white matter abnormalities in normal aging. *Neuropsychology*. 2000; 14(2):224-232.
11. Pedroso RV, Coelho FG, Santos-Galduróz RF, Costa JLR, Gobbi S, Stella F. Balance, executive functions and falls in elderly with Alzheimer's disease (AD): a longitudinal study. *Arch Gerontol Geriatr*. 2012;54(2):348-351. doi:10.1016/j.archger.2011.05.029.
12. Raz N, Lindenberger U, Rodrigue KM, et al. Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cereb Cortex*. 2005;15(11): 1676-1689. doi:10.1093/cercor/bhi044.
13. Fischer BL, Gleason CE, Gangnon RE, Janczewski J, Shea T, Mahoney JE. Declining cognition and falls: role of risky performance of everyday mobility activities. *Phys Ther*. 2014;94(3): 355-362. doi:10.2522/ptj.20130195.
14. Anstey KJ, Wood J, Kerr G, Caldwell H, Lord SR. Different cognitive profiles for single compared with recurrent fallers without dementia. *Neuropsychology*. 2009;23(4):500-508. doi:10.1037/a0015389.
15. Berg KO, Maki BE, Williams JI, Holliday PJ, Wood-Dauphinee SL. Clinical and laboratory measures of postural balance in an elderly population. *Arch Phys Med Rehabil*. 1992;73(11): 1073-1080.
16. Muir SW, Berg K, Chesworth B, Klar N, Speechley M. Balance impairment as a risk factor for falls in community-dwelling older adults who are high functioning: a prospective study. *Phys Ther*. 2010;90(3):338-347. doi:10.2522/ptj.20090163.
17. Lajoie Y, Gallagher SP. Predicting falls within the elderly community: comparison of postural sway, reaction time, the Berg Balance Scale and the Activities-Specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. *Arch Gerontol Geriatr*. 2004;38(1):11-26. doi:10.1016/S0167-4943(03)00082-7.
18. Rose DJ. *Fallproof!: A Comprehensive Balance and Mobility Training Program*. 2nd ed. Champaign, IL: Human Kinetics; 2010.
19. Glorioso C, Sibille E. Between destiny and disease: genetics and molecular pathways of human central nervous system aging. *Prog Neurobiol*. 2011;93(2):165-181. doi:10.1016/j.pneurobio.2010.11.006.
20. Thorbahn LDB, Newton RA. Use of the berg balance test to predict falls in elderly persons. *Phys Ther*. 1996;76(6):576-583. doi:10.1093/ptj/76.6.576.
21. Tangen GG, Engedal K, Bergland A, Moger TA, Mengshoel AM. Relationships between balance and cognition in patients with subjective cognitive impairment, mild cognitive impairment, and Alzheimer's disease. *Phys Ther*. 2014;94(8):1123-1134. doi:10.2522/ptj.20130298.
22. Graafmans WC, Ooms ME, Hofstee HM, Bezemer PD, Bouter LM, Lips P. Falls in the elderly: a prospective study of risk factors and risk profiles. *Am J Epidemiol*. 1996;143(11):1129-1136. doi:10.1093/oxfordjournals.aje.a008690.
23. Saverino A, Waller D, Rantell K, Parry R, Moriarty A, Playford ED. The role of cognitive factors in predicting balance and fall risk in a neuro-rehabilitation setting. *PLoS One*. 2016;11(4): e0153469. doi:10.1371/journal.pone.0153469.
24. Singapore Department of Statistics. *National Statistical Standards: Recommendations on Definition and Classification of Age*. 2007, https://www.singstat.gov.sg/docs/default-source/default-document-library/methodologies_and_standards/standards_and_classifications/nsa.pdf.
25. Folstein ME, Folstein SE, McHugh PR. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975;12(3):189-198.
26. Tombaugh TN, McIntyre NJ. The Mini-Mental State Examination: a comprehensive review. *J Am Geriatr Soc*. 1992;40(9): 922-935. doi:10.1111/j.1532-5415.1992.tb01992.x.
27. Kukull WA, Larson EB, Teri L, Bowen J, McCormick W, Pfanschmidt ML. The Mini-Mental State Examination score and the clinical diagnosis of dementia. *J Clin Epidemiol*. 1994;47(9): 1061-1067. doi:10.1016/0895-4356(94)90122-8.
28. Jacome C, Cruz J, Oliveira A, Marques A. Validity, reliability, and ability to identify fall status of the Berg Balance Scale, BESTest, mini-BESTest, and brief-BESTest in patients with COPD. *Phys Ther*. 2016;96(11):1807-1815. doi:10.2522/ptj.20150391.

29. Berg K. Measuring balance in the elderly: preliminary development of an instrument. *Physiother Can*. 1989;41(6):304-311. doi:10.3138/ptc.41.6.304.
30. Shumway-Cook A, Baldwin M, Polissar NL, Gruber W. Predicting the probability for falls in community-dwelling older adults. *Phys Ther*. 1997;77(8):812-819. doi:10.1093/ptj/77.8.812.
31. Jeon Y, Kim G. Comparison of the Berg Balance Scale and Fullerton Advanced Balance Scale to predict falls in community-dwelling adults. *J Phys Ther Sci*. 2017;29(2):232-234. doi:10.1589/jpts.29.232.
32. Department of Statistics Singapore. *Population Trends, 2015*; 2015. www.singstat.gov.sg.
33. Taylor ME, Delbaere K, Lord SR, Mikolaizak AS, Close JC. Physical impairments in cognitively impaired older people: implications for risk of falls. *Int Psychogeriatr*. 2013;25(1):148-56. doi:10.1017/S1041610212001184.
34. Härlein J, Halfens RJ, Dassen T, Lahmann NA. Falls in older hospital inpatients and the effect of cognitive impairment: a secondary analysis of prevalence studies. *J Clin Nurs*. 2011;20(1-2):175-183. doi:10.1111/j.1365-2702.2010.03460.x.
35. Arguvanli S, Akin S, Deniz Safak E, et al. Prevalence of cognitive impairment and related risk factors in community-dwelling elderly in Kayseri, Turkey. *Turk J Med Sci*. 2015;45(5):1167-1172. doi:10.3906/sag-1406-149.
36. Seeman TE, Huang M, Bretsky P, Crimmins E, Launer L, Guralnik JM. Education and APOE-e4 in longitudinal cognitive decline: Macarthur Studies of Successful Aging. *J Gerontol B Psychol Sci Soc Sci*. 2005;60(2):74-83. doi:10.1093/geronb/60.2.P74.
37. Albert MS. How does education affect cognitive function?. *Ann Epidemiol*. 1995;5(1):76-78. doi:10.1016/1047-2797(94)00044-T.
38. Eggenberger P, Wolf M, Schumann M, de Bruin ED. Exergame and balance training modulate prefrontal brain activity during walking and enhance executive function in older adults. *Front Aging Neurosci*. 2016;8:66. doi:10.3389/fnagi.2016.00066.
39. Mitchell AJ. A meta-analysis of the accuracy of the Mini-Mental State Examination in the detection of dementia and mild cognitive impairment. *J Psychiatr Res*. 2009;43(4):411-431. doi:10.1016/j.jpsychires.2008.04.014.

III

IMMEDIATE EFFECTS OF WEARING KNEE LENGTH SOCKS DIFFERING IN COMPRESSION LEVEL ON POSTURAL REGULATION IN COMMUNITY-DWELLING, HEALTHY, ELDERLY MEN AND WOMEN

by

Woo, M. T., Davids, K., Liukkonen, J., Chow, J. Y.,
& Jaakkola, T. 2018

Gait & Posture, 66, 63 – 69

https://doi.org/10.1016/j.gaitpost.2018.08.011

Gait & Posture 66 (2018) 63–69

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Immediate effects of wearing knee length socks differing in compression level on postural regulation in community-dwelling, healthy, elderly men and women

Mei Teng Woo[a,b,*], Keith Davids[c], Jarmo Liukkonen[a], Jia Yi Chow[d], Timo Jaakkola[a]

[a] Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland
[b] School of Sports, Health and Leisure, Republic Polytechnic, Singapore
[c] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, United Kingdom
[d] Physical Education and Sports Science, National Institute of Education, Nanyang Technological University, Singapore

ARTICLE INFO

Keywords:
Elderly individuals
Knee length socks
Compression
Postural regulation

ABSTRACT

Background: Stimulation of lower limbs' cutaneous receptors and mechanoreceptors through compression garments could potentially increase somatosensory system efficiency and aid postural regulation in elderly individuals.
Research question: This study examined immediate effects of wearing knee length socks (KLS) of various compression levels on somatosensory function in community-dwelling healthy elderly men and women during a double-limb standing, balancing task.
Methods: A total of forty-six elderly participants (Male = 23), aged between 65 and 84 years old, randomly selected from the Singapore community-dwelling, healthy population. Three treatment interventions (wearing clinical compression socks; wearing non-clinical compression socks; wearing commercial socks) and one control condition (barefoot), in a counterbalanced order, were administered to participants while they performed a 30-s Romberg test, with four levels of performance difficulty: (1) standing on a stable surface with vision (SO); (2) a stable surface without vision (SC); (3) a foam surface with vision (FO); and (4), a foam surface without vision (FC).
Results: Results showed that immediate effects of applying KLS of various compression levels significantly reduced sway area, trace length, velocity, and anterior-posterior (AP) sway as compared to barefoot condition (control) during the FO task condition.
Significance: This finding indicates the positive immediate effects of garments on somatosensory system function and postural regulation in the elderly men and women, especially when standing on the unstable surface. Wearing compression KLS could be included as a viable intervention on top of other forms of balance training to reduce risk of falling in elderly people.

1. Introduction

Postural regulation and stability of balance are affected by types of standing surfaces and somatosensory system function of an individual [1]. Standing on unstable surfaces, like foam surfaces, have revealed the important role of somatosensory information in postural regulation and balance [1,2]. Studies have suggested that postural sway increases for balance regulation, especially when individuals are standing on a foam surface [1,3]. Somatosensory function is important to study since neurodegeneration can result in age-related declines in postural regulation due to reduction in cognitive and sensory system capacities [4]. For example, ageing can result in decreased sensitivity to sensory information and motor output, slowing of cognitive capacities, increased reaction time, and decreased spinal-stretch reflex system function [4–6]. These deteriorations could possibly put elderly individuals at greater risk of falls [4]. To address the issue of decreased functionality of postural regulation, lower-limb stimulation strategies (LLS) such as wearable garments (braces & socks) [7,8], textured insoles [2,8], and application of Stochastic Resonance (SR) [8] have demonstrated some positive effects on postural regulation during balancing tasks in middle-aged and older adults (65 years and above). On the other hand, postural regulation and stability are affected by the types of standing surfaces

* Corresponding author at: Faculty of Sport and Health Sciences, University of Jyväskylä, P.O. Box 35 (L), FI- 40014, Finland.
E-mail address: woo_mei_teng@rp.edu.sg (M.T. Woo).

https://doi.org/10.1016/j.gaitpost.2018.08.011
Received 6 May 2018; Received in revised form 8 July 2018; Accepted 13 August 2018
0966-6362/

and the visual conditions available to a person [1]. Specifically, foam surfaces are commonly used to disrupt somatosensory information [1,2]. With the absence of vision, studies have suggested that postural sway increases, especially when individuals are standing on a foam surface [1,3]. However, further investigation of elderly samples are needed to ascertain whether postural regulation can be enhanced during static balance, when standing on different surfaces and under varied visual conditions (e.g., with and without), when wearing compression socks. Therefore, this study aimed to investigate the effects of compression wearable garments on somatosensory feedback in static balance task, under different standing surfaces and vision conditions (e.g., with and without), in elderly people.

An ecological dynamics framework has been proposed to account for how compression and textured materials can support the exploitation of sensorimotor system noise to enhance functional performance. Davids et al. (2003) [9] argued that the functional role of variability induced in the sensorimotor system by textured insoles, acts as a form of "essential noise" which helps individuals regulate actions. They suggested that the addition of intermittent, intermediate levels of noise, via textured insoles, may help performers to pick up information from the background signals to enhance perception of somatosensory feedback [9]. Effects of wearable garments could be related to neuromotor function, specifically invoking the Hoffmann Reflex (H-reflex), an indirect measure of motorneuron excitability [10]. It has been reported that wearing an ankle brace increases motorneuron excitation in the afferent system at the Peroneus Longus muscle [10], providing additional active impact for proprioceptive control of movement in the ankle dorsiflexor muscles [11]. Evidence from research on performance of a younger, athletic population performing a sport action implies that stimulation of the sensory system in the lower limbs by wearable garments (e.g., compression socks and textured insoles) could potentially increase the efficiency of somatosensory system function and aid postural regulation of elderly individuals [12].

It has also been suggested that application of stimulation, provided by adding pressure, texture nodules, and velcro strapping on the cutaneous, joints, and muscle receptors of the lower limbs could enhance the level of sensorimotor system noise to improve perceptual-motor system functionality [2,8,9,13,14]. A postulation is that stimulation of the muscle spindles and mechanoreceptors along the shank, when wearing compression socks, enhances postural regulation by contortion and disturbances of haptic system receptors in the skin and soft tissue of the lower limbs [8]. Recent investigations have suggested some beneficial effects of wearing a knee compressive sleeve in reducing postural sway in the anteroposterior (AP) direction [15] and donning a compression stocking reduced the CoP trajectory amplitude [16]. In an elderly sample, Losa Iglesia (2012) [17] reported that wearing socks reduced sway areas compared to when the same participants regulated posture in a barefoot condition. These initial findings suggest that more research is needed to address the role of wearing compression socks in stimulating somatosensory system feedback that emerges from pressure on cutaneous and joint receptors in the lower legs in the elderly population.

Furthermore, no studies have addressed the question of effects of LLS related to gender differences associated with age-related degeneration of the perceptual-motor system. It is possible that elderly men and women respond differently, based on fundamental differences in morphology, exemplified by variations in brain structure and function, musculature, and the sensory systems [18]. For example, some studies have identified a possible gender effect with elderly women displaying greater CoP sway values [19], lower balance scores [20], and shorter nerve conduction pathways [18] than elderly men. Wearing compression garments could potentially enhance the sensitivity of the cutaneous and mechanoreceptors in elderly females, reducing their falls risk, by indirectly enhancing their postural regulation capacity.

Therefore, the current study sought to understand whether wearing compressive knee length socks (KLS) would enhance the stimulation of mechanoreceptors in the lower limbs of elderly men and women, helping these community-dwelling individuals to achieve better postural regulation, and potentially forming a strategy to reduce risk of falling. We sought to add to the literature by discerning the impact of low cost, easily implemented compression materials, on somatosensory function and postural regulation in elderly males and females. The specific aim of this study was to examine immediate effects of wearing KLS of various compression levels on postural regulation under four levels of performance difficulty, in community-dwelling healthy elderly men and women, during double-limb standing, balancing task. It was hypothesized that wearing compression KLS would reduce postural sway, with gender-based differences being observed in these community-dwelling elderly men and women.

Table 1
Participants' Demographic.

	Men (N = 23)	Women (N = 23)
Age (years)	75.2 ± 5.1	72.8 ± 5.8
Height (cm)	162.3 ± 6.4	153.7 ± 6.2
Weight (kg)	57.9 ± 9.5	59.8 ± 11.2
Berg Balance Scale (Scores)	50.9 ± 4.3	50.6 ± 4.4
Mini-Mental State Examination (Scores)	25.7 ± 1.4	26.4 ± 1.9

2. Methods

2.1. Participants

A total of 46 (Male = 23) community-dwelling elderly individuals (Table 1), were randomly selected based on specific inclusion criteria, from the profiling of Singapore community-dwelling elderly people project [20]. Specific inclusion criteria were ability to walk independently without using any assistive devices (e.g., walking stick; umbrella), no history of falling in the past 12 months, Berg Balance task Score > 40 (normal), and Mini-Mental State Examination (MMSE) score > 24 (normal). Exclusion criteria were: evidence of muscular and neurological diseases, recent stroke events (< 18 months), and brain injuries. Voluntary and informed consent was obtained from all 46 participants, and the procedures used in the study were approved and in accordance with the ethical guidelines of the research ethics committee of Nanyang Technological University, Singapore.

2.2. Apparatus and tasks

Three treatment interventions (wearing clinical compression KLS; wearing non-clinical compression KLS; wearing commercial KLS) and one control condition (barefoot), in a counterbalanced order, were administered to participants while they performed a double-limb standing balance task. In testing we used KLS with clinical level compression KLS (CC) of 20–30 mmHg pressure (Zeropoint, Finland), KLS with non-clinical level compression (NCC) of 8–15 mmHg (X-bionic, Switzerland), and non-compression (NC) models commercial KLS (Mizuno, Japan) of similar thickness. The purpose of including different types of KLS was to gain insights into effects of wearing garments of varying compression levels. We sought to discern whether the degree of contortion of lower limb tissue, by different compression properties, might influence postural regulation function in elderly males and females. The tasks required participants to perform a 30-s Romberg test on a balance platform (Hur, Finland) under two vision conditions (eyes open and closed) and on two standing surfaces (stable and foam) inside a laboratory. The dimension of the foam was 50 × 50 × 10 cm and the density was at 30 kg/m^3.

The four levels of performance difficulty task conditions were standing on: (1) a stable surface with eyes open (SO); (2) a stable surface with eyes closed (SC); (3) a foam surface with eyes open (FO); and (4), a foam surface with eyes closed (FC). All treatment interventions and task conditions were presented in a random order for each participant.

2.3. Procedure

A repeated-measures design was used to determine effects on balance and postural control of four different treatment conditions – wearing CC KLS; wearing NCC KLS; wearing NC KLS; barefoot. The sequences of the testing interventions and the task conditions were randomised by using Microsoft Excel to prevent carryover/order effects.

For the 30-s Romberg test, participants were instructed to stand upright and as still as possible with feet together and the arms by the side. For the eyes open condition, participants were asked to look straight ahead to a reference point on a blank wall, marked at eye level, and it was about 1.5 m away from the balance platform. For the unstable surface, a 10-cm thick foam pad was placed on top of the balance platform to create a more challenging surface for the participants.

Before data collection, participants undertook two trials of the static balance task to familiarize themselves with each of the four task conditions– SO, SC FO, FC. For every treatment intervention, participants were required to perform 2 trials for each of the task conditions. Participants were given a sufficient rest period (~ 2 min) between each treatment intervention. The tests were repeated if participants lost balance on the platform.

2.4. Data processing and Statistical analysis

Centre of pressure data were collected at a sampling frequency of 100 Hz, accumulating to 3000 data points for each condition. The parameters were the 90% confidence elliptical area (C90 sway area), trace length (TL, the total length of the CoP path), sway velocity, range of anterior–posterior (AP) and medial–lateral (ML) CoP displacement, AP and ML standard deviation (SD). Observed increases in value of these parameters were associated with a greater risk of falling [21]. It has been reported that the sway area, trace length, and sway velocity are the most reliable CoP stabilometric parameters in measuring postural stability [6]. All data were analyzed by using nonparametric statistical tests due to abnormal data distributions. SPSS software (version 24.0) was used for statistical analysis. All measurements across the treatment interventions were compared using a Friedman test – K related samples. If statistically significant results were found during the Friedman test, Wilcoxon sign test was conducted to further identify which treatment intervention resulted in a significant effect. Results were reported as means and standard deviation (SD). Alpha level was set at < 0.05 for all statistical analyses.

3. Results

3.1. Postural sway (C90) area

For the female group, the Friedman test revealed significant differences across the treatment interventions on the foam surface with eyes open ($p = 0.007$) (Fig. 1). Post hoc analysis showed that the sway area in that group was significantly lower while wearing the NCC ($p = 0.013$) and NC ($p = 0.016$) KLS compared to the barefoot condition. No statistically significant effects were found across the treatment interventions in men.

3.2. Trace length

For the female group, the Friedman test revealed significant differences across the treatment interventions on the foam surface with eyes open ($p = 0.007$), but not in the other three task conditions – SO, SC and FC (Fig. 2). Post hoc analysis showed that trace length was significantly shorter while participants wore the NCC KLS ($p = 0.013$), compared to the barefoot condition for the FO task condition. No statistically significant effects were found across the treatment interventions in men.

3.3. Sway velocity

The Friedman test revealed significant differences across the treatment interventions ($p = 0.027$) in the female group in the FO task condition (Fig. 3). Post hoc analysis showed that sway velocity was significantly lower while wearing the CC and NCC KLS ($p = 0.013$) compared to the barefoot condition. No statistically significant effects were found across the treatment interventions in men.

3.4. Anterior–posterior (AP) postural sway and AP SD

There were significant differences across the treatment interventions in AP sway on both stable ($p = 0.043$) and foam ($p = 0.027$) surfaces, with eyes open (Table 2) in the elderly males. In the SO task condition, post hoc analysis revealed that CC KLS significantly decreased AP sway compared to when wearing NCC KLS ($p = 0.013$) and when standing barefoot ($p = 0.039$) in the elderly men. The same beneficial effect of wearing CC KLS was observed in the FO condition. A significant difference across treatment interventions was observed on APSD ($p = 0.012$) in the SC condition. However, no significant differences were found in all treatment interventions and all task conditions on AP sway and AP SD values in the women.

3.5. Medial–lateral (ML) postural sway and ML SD

There were no differences across the treatment interventions on ML sway and ML SD in the elderly men (Table 2). A significant difference across treatment conditions was observed in MLSD ($p = 0.012$) in SC task in the women.

4. Discussion

The aim of this study was to examine immediate effects of wearing KLS of various compression levels on somatosensory function, during a double-limb standing balancing task. The results of this study support our hypothesis on the beneficial effects of wearing compression KLS on postural regulation in community-dwelling elderly men and women. In elderly men, wearing CC and NCC KLS decreased postural sway, mainly in the AP direction in both SO and FO task conditions. Similarly, wearing KLS, particularly non-clinical compression, reduced sway area, trace length and sway velocity while standing on the foam surface with eyes open (FO) in the elderly women. There were no significant beneficial effects of all levels of KLS observed in the FC condition in both elderly men and women.

Consistent with findings of previous studies, use of lower-limb stimulation strategies decreased postural sway for elderly participants wearing textured insoles (see Qiu et al., 2012) [2] and hard insoles [17]. Our results support the idea that compression wearable garments can enhance the functioning of the postural regulation system by reducing sway [8,14,16,22]. Wearing CC and NCC KLS are deemed to be beneficial perhaps due to their capacity to support exploitation of the available “sensorimotor system noise” to enhance perception of proprioceptive and haptic information during performance of complex tasks (for example, maintaining upright stance while standing on an unstable surface). Furthermore, wearing compression KLS yielded similar effects as balance training interventions (electrical stimulation) in improving postural stability in elderly people [23,24]. Perhaps wearing compression KLS may increase motorneuron excitability of H-reflex, as suggested by Nishikawa and Grabiner (1999) [10] and down-modulated the Hoffmann Reflex (H-reflex). Therefore, wearing compression KLS, which covered most of the lower legs, seemed to stimulate the various cutaneous mechanoreceptors, motor neurons, and muscle

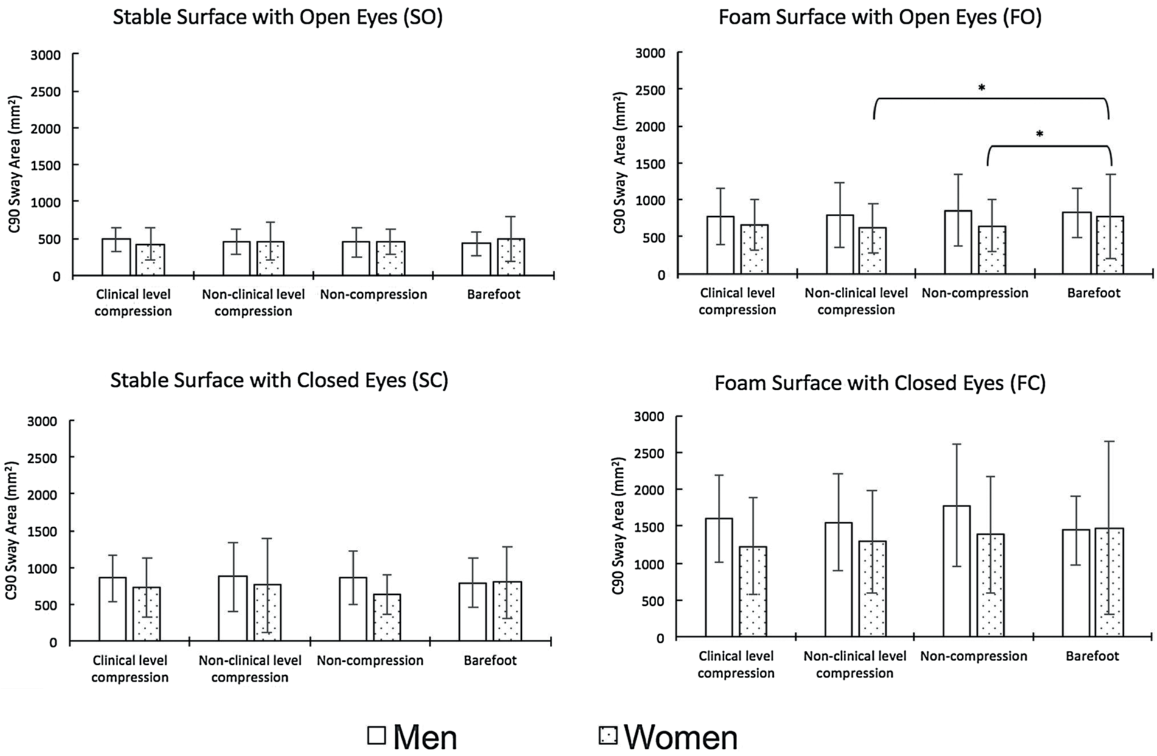


Fig. 1. Mean (SD) C90 area for the elderly men and women during the four task conditions.
* Significantly lower than barefoot.

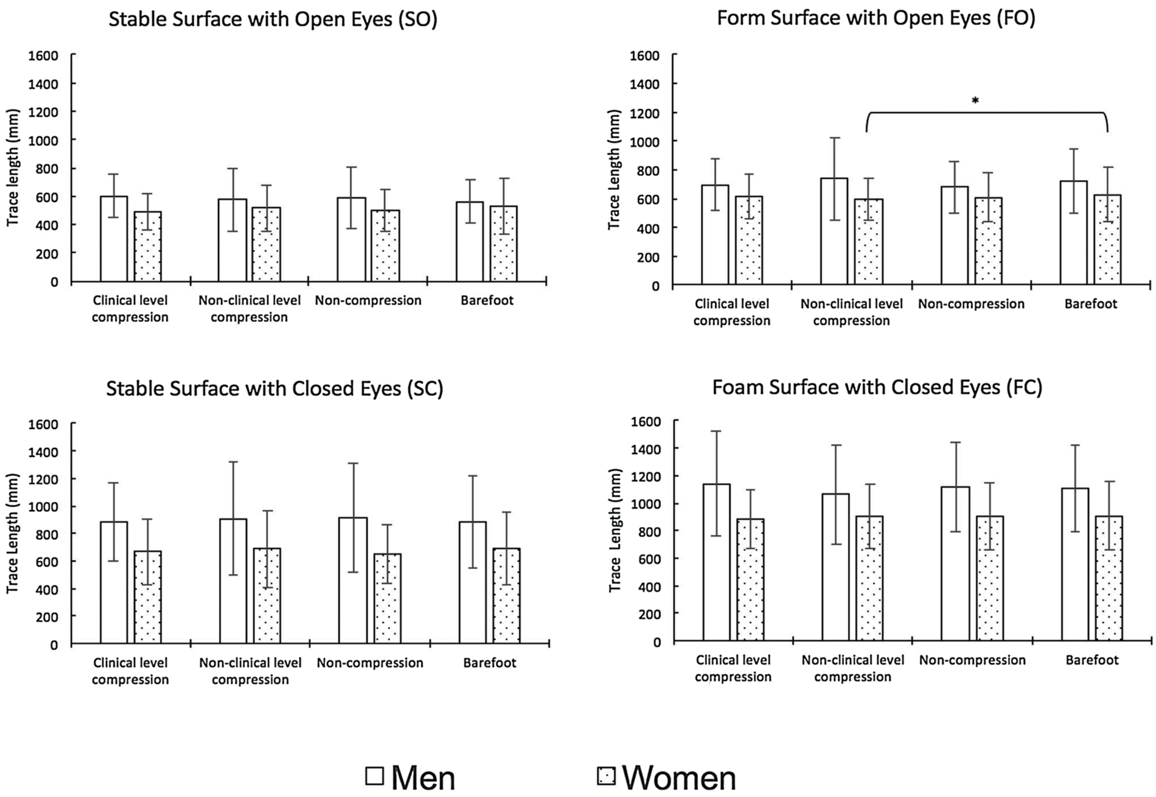


Fig. 2. Mean (SD) trace length for the elderly men and women during the four task conditions.
* Significantly lower than barefoot.

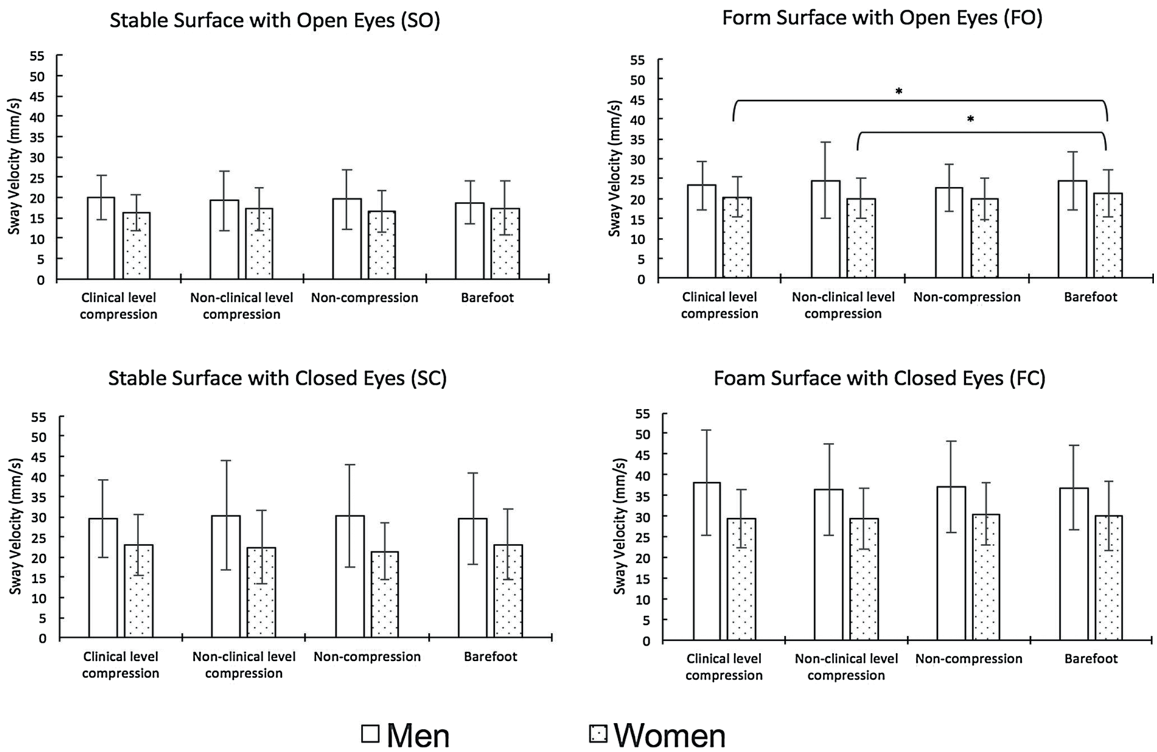


Fig. 3. Mean (SD) sway velocity for the elderly men and women during the four task conditions.

proprioceptors along the shanks, and could potentially form a strategy to ameliorate negative effects of ageing on the postural control system and reduce risk of falling.

The amplitude and conduction velocity of motor and sensory nerves have been found to significantly differ with gender [25]. This effect could be potentially attributed to the gender-based differences observed from wearing the compression KLS in our study. In agreement with our findings, Olchowik et al. (2015) [26] found that men displayed less postural sway than women in the AP direction. Our findings provided new insights, indicating that wearing compression KLS, is beneficial to men, as supported by the decrease in the sway distance in the AP direction. Furthermore, we found that women displayed positive performance outcome in many COP variables such as sway area, trace length, and sway velocity. This observation could be due to the possibility that women use the ankle strategy (to regulate balance) more effectively than men [25,26]. Wearing compression KLS seems to aid the ankle control strategy by stimulating the cutaneous and mechanoreceptors around the ankle joint. An issue requiring further research concerns the suggestion that compression garment manufacturers may improve sock design, by concentrating the stimulating material (by increasing textured undulations) surrounding the ankle and at the anterior-posterior aspects of the compression socks.

In this study, KLS enhanced postural regulation performance in a challenging condition – during upright balance on a foam (unstable) surface with eyes open (i.e., availability of vision), supporting findings with textured insoles reported by Qiu et al. (2012). The role of somatosensory feedback is assumed to be more important when standing on an unstable surface [1,3]. In the current study, wearing compression KLS seemed to provide necessary sensory information to the Central Nervous System (CNS) and facilitated the perceptual regulation of stance [3] when the somatosensory system is compromised. In contrast to data of Qiu et al. (2017) [2], our study showed no immediate beneficial effects of wearing compression KLS when both vision and somatosensory are compromised [i.e., standing on a foam surface with eyes closed (FC)]. Effects of these sensory perturbations seemed to be too severe for mediation by wearing compression garments, although potential long term effects may need to be assessed. This finding could imply that the somatosensory system stimulation provided by wearing compression KLS is not sufficient to yield beneficial effects when both vision and somatosensory systems are compromised. However, more studies are needed to confirm the beneficial effects of wearing compression KLS on postural regulation in the FC condition.

To summarise, our study showed that wearing compression KLS significantly improved the balance performance in FO task condition. It was observed that men and women responded differently to the effects of wearing compression KLS on postural regulation. Wearing compression KLS could be used as a medium to reduce risk of falling and enhance postural control and function of the perceptual-motor systems. A limitation of this study includes the absence of an assessment of the muscle strength capacity of our participants and it is unknown whether individual variations in lower limb muscle strength affected performance outcomes, if at all. Future studies could include some form of measurement of muscle strength to determine the effect of muscle strength coupled with the use of KLS on the balance tasks. In addition, there could also be an emphasis on examining the long-term effects of wearing compression KLS on postural regulation and dynamic tasks (e.g., walking, sliding), and the immediate effects of wearing compression KLS in specific groups of elderly individuals with debilitating conditions, such as diabetes, Parkinson Disease and peripheral neuropathy.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgements

We acknowledge the support from the compression sock manufacturer: ZeroPoint, Finland (www.zp.fi).

Table 2
Balance Measures of postural difficulty levels in elderly men and women (Mean ± SD).

	Men (N = 23)					Women (N = 23)				
	Clinical level compression (> 20 mmHg)	Non-clinical level compression (8 - 15 mmHg)	Non-compression	Barefoot	p-value	Clinical level compression (> 20 mmHg)	Non-clinical level compression (8 - 15 mmHg)	Non-compression	Barefoot	p-value
(a) Stable Surface with Eyes Open (SO)										
Anterior–posterior (AP) Sway (mm)	33.4 ± 14.67*	38.66 ± 16.28	35.93 ± 15.47	36.75 ± 17.25	< 0.05	46.45 ± 19.67	42.67 ± 17.62	42.23 ± 19.9	42.13 ± 21.03	> 0.05
Anterior–posterior (AP) SD (mm)	5.3 ± 1.29	5.08 ± 1.12	4.98 ± 1.27	4.99 ± 1.12	> 0.05	5.06 ± 1.46	5.07 ± 1.54	5.22 ± 1.26	5.36 ± 1.96	> 0.05
Medial–lateral (ML) Sway (mm)	6.18 ± 5.43	6.63 ± 4.64	7.34 ± 4.93	7.09 ± 5.53	> 0.05	7.21 ± 4.25	6.72 ± 5.23	7.76 ± 5.76	7.6 ± 5.43	> 0.05
Medial–lateral (ML) SD (mm)	6.26 ± 0.97	6.22 ± 1.32	6.27 ± 1.75	5.91 ± 1.12	> 0.05	5.67 ± 1.4	6.28 ± 1.69	6.06 ± 1.16	6.35 ± 1.52	> 0.05
(b) Form Surface with Eyes Open (FO)										
Anterior–posterior (AP) Sway (mm)	53.67 ± 27.38**	66.44 ± 26.31	60.04 ± 28.12	57.56 ± 27.95**	< 0.05	67.14 ± 30.04	67.55 ± 29.61	70.49 ± 25.42	66.07 ± 31.86	> 0.05
Anterior–posterior (AP) SD (mm)	7.06 ± 2.01	6.92 ± 1.91	7.64 ± 3.01	7.49 ± 2.34	> 0.05	6.23 ± 1.69	6.13 ± 1.7	6.32 ± 1.52	6.83 ± 2.32	> 0.05
Medial–lateral (ML) Sway (mm)	10.45 ± 5.75	9.99 ± 5.82	8.98 ± 5.06	9.37 ± 5.21	> 0.05	9.25 ± 6.23	11.59 ± 6.77	9.44 ± 6.8	9.08 ± 6.66	> 0.05
Medial–lateral (ML) SD (mm)	7.58 ± 1.52	7.75 ± 2.14	7.62 ± 1.77	7.73 ± 1.77	> 0.05	7.07 ± 1.58	7.03 ± 1.88	7 ± 1.72	7.29 ± 2.17	> 0.05
(c) Stable Surface with Closed Eyes (SC)										
Anterior–posterior (AP) Sway (mm)	29.98 ± 13.75	34 ± 15.28	33.4 ± 16.85	33.4 ± 15.49	> 0.05	44.93 ± 20.97	43.35 ± 18.43	35.65 ± 18.07	41.11 ± 20.47	> 0.05
Anterior–posterior (AP) SD (mm)	7.12 ± 1.22	6.93 ± 1.83#	7.18 ± 1.82	6.55 ± 1.54#	< 0.05	6.5 ± 1.82	6.35 ± 2.22	6.07 ± 1.53	6.53 ± 2.28	> 0.05
Medial–lateral (ML) Sway (mm)	7.13 ± 4.15	7.8 ± 4.67	7.35 ± 5.18	7.07 ± 4.43	> 0.05	5.78 ± 3.21	6.71 ± 2.89	6.74 ± 4.08	7.17 ± 6.38	> 0.05
Medial–lateral (ML) SD (mm)	8.32 ± 2.31	8.54 ± 2.27	8.1 ± 1.93	8.35 ± 2.18	> 0.05	7.91 ± 2.46	7.68 ± 2.72	7.21 ± 2.06##	8.26 ± 2.46	< 0.05
(d) Foam Surface with Closed Eyes (FC)										
Anterior–posterior (AP) Sway (mm)	56.13 ± 24.84	66.07 ± 26.37	62.46 ± 27.31	60.68 ± 30.67	> 0.05	67 ± 28.08	67.7 ± 28.31	68.71 ± 24.42	65.12 ± 24.89	> 0.05
Anterior–posterior (AP) SD (mm)	10 ± 2.18	9.5 ± 1.98	10.25 ± 2.77	9.34 ± 1.84	> 0.05	8.58 ± 3.03	8.95 ± 2.66	9.2 ± 2.71	9.31 v 3.51	> 0.05
Medial–lateral (ML) Sway (mm)	11.07 ± 5.79	10.13 ± 5.34	10.25 ± 4.61	8.83 ± 4.77	> 0.05	10.41 ± 6.01	13.81 ± 7.62	9.57 ± 5.71	10.09 ± 6.41	> 0.05
Medial–lateral (ML) SD (mm)	10.97 ± 2.16	11.11 ± 2.95	11.73 ± 3.15	10.8 ± 2.42	> 0.05	9.43 ± 2.39	9.89 ± 2.38	9.74 ± 3.07	10 ± 3.1	> 0.05

* A significant difference between Non-clinical level compression and barefoot.
** Significantly lower than Non-clinical level compression.
# Significantly lower than Non-compression.
A significant difference between non-compression and barefoot.

This work was supported by the National Institute of education (NIE) Academic Research Fund [grant numbers (ACRF) x RI 8/13 CJY].

References

[1] M. Patel, P.A. Fransson, D. Lush, S. Gomez, The effect of foam surface properties on postural stability assessment while standing, Gait Posture 284 (2008) 649–656.

[2] F. Qiu, M.H. Cole, K.W. Davids, E.M. Hennig, P.A. Silburn, H. Netscher, G.K. Kerr, Enhanced somatosensory information decreases postural sway in older people, Gait Posture 354 (2012) 630–635.

[3] N. Vuillerme, N. Pinsault, Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue, Exp. Brain Res. 1833 (2007) 323–327.

[4] D.J. Rose, Fallproof!: a Comprehensive Balance and Mobility Training Program, 2nd ed., Human Kinetics, Champaign, IL, 2010.

[5] T. Miyoshi, D. Nozaki, H. Sekiguchi, T. Kimura, T. Sato, T. Komeda, K. Nakazawa, H. Yano, Somatosensory graviception inhibits soleus H-reflex during erect posture in humans as revealed by parabolic flight experiment, Exp. Brain Res. 1501 (2003) 109–113.

[6] B. Seigle, S. Ramdani, P.L. Bernard, Dynamical structure of center of pressure fluctuations in elderly people, Gait Posture 302 (2009) 223–226.

[7] M.T. Woo, K. Davids, J. Liukkonen, T. Jaakkola, J.Y. Chow, Effects of textured compression socks on postural control in physically active elderly individuals, Procedia Eng. 72 (2014) 162–167.

[8] M.T. Woo, K. Davids, J. Liukkonen, D. Orth, J.Y. Chow, T. Jaakkola, Effects of different lower-limb sensory stimulation strategies on postural regulation—a systematic review and meta-analysis, PLoS ONE 123 (2017) e0174522.

[9] K. Davids, R. Shuttleworth, C. Button, I. Renshaw, P. Glazier, "Essential noise" – enhancing variability of informational constraints benefits movement control: a comment on waddington and adams, Br. J. Sports Med. 38 (2003) 601–605.

[10] T. Nishikawa, M.D. Grabiner, Peroneal motoneuron excitability increases immediately following application of a semirigid ankle brace, J. Orthop. Sports Phys. Ther. 293 (1999) 168–176.

[11] L.E. Larsen, L.A. Jakobsen, A. Jensen, B.M. Lambden, M.R. Sørensen, J. Ellrich, Inhibition of soleus Hoffmann reflex by ankle–foot orthosis application in healthy volunteers, Prosthet. Orthot. Int. 396 (2015) 444–453.

[12] H. Hasan, K. Davids, J.Y. Chow, G. Kerr, Compression and texture in socks enhance football kicking performance, Hum. Mov. Sci. 48 (2016) 102–111.

[13] J.M. Hijmans, J.H.B. Geertzen, P.U. Dijkstra, K. Postema, A systematic review of the effects of shoes and other ankle or foot appliances on balance in older people and people with peripheral nervous system disorders, Gait Posture 252 (2007) 316–323.

[14] D. Orth, K. Davids, J. Wheat, L. Seifert, J. Liukkonen, T. Jaakkola, D. Ashford, G. Kerr, The role of textured material in supporting perceptual-motor functions, PLoS ONE 84 (2013) e60349.

[15] M.S. Kuster, K. Grob, M. Kuster, G.A. Wood, A. Gächter, The benefits of wearing a compression sleeve after ACL reconstruction, Med. Sci. Sports Exerc. 313 (1999) 368–371.

[16] N. Genthon, E. Bouvat, J.J. Banihachemi, J. Bergeau, A. Abdellaoui, P.R. Rougier, Lateral ankle sprain alters postural control in bipedal stance: part 2 sensorial and mechanical effects induced by wearing an ankle orthosis, Scan. J. Med. Sci. Sports 20 (2010) 255–261.

[17] Losa Iglesias, Becerrode Bengoa ME, Ricardo Vallejo, D. Palacios Peña, Impact of soft and hard insole density on postural stability in older adults, Geriatr. Nurs. (Minneap) 334 (2012) 264.

[18] J.M. Stephen, D. Ranken, E. Best, J. Adair, J. Knoefel, S. Kovacevic, D. Padilla, B. Hart, C.J. Aine, Aging changes and gender differences in response to median nerve stimulation measured with MEG, Clin. Neurophysiol. 1171 (2006) 131–143.

[19] J. Kim, G. Eom, C. Kim, D. Kim, J. Lee, B.K. Park, J. Hong, Sex differences in the postural sway characteristics of young and elderly subjects during quiet natural standing, Geriatr. Gerontol. Int. 102 (2010) 191.

[20] M.T. Woo, K. Davids, J. Liukkonen, J.Y. Chow, Jaakkola T. Falls, Cognitive function, and balance profiles of Singapore community-dwelling elderly individuals: key risk factors, Geriatr. Orthop. Surg. Rehabil. 84 (2017) 256–262.

[21] I. Melzer, I. Kurz, L.I.E. Oddsson, A retrospective analysis of balance control parameters in elderly fallers and non-fallers, Clin. Biomech. 2510 (2010) 984–988.

[22] M.R. Kunzler, L.M. Lopes, L.S. Ueda, M.A. de Britto, F.P. Carpes, Does skin stimulation compensate impairments in postural control after ankle plantar flexors fatigue? Gait Posture 374 (2013) 611–614.

[23] W. Taube, M. Gruber, A. Gollhofer, Spinal and supraspinal adaptations associated with balance training and their functional relevance, Acta Physiol. 1932 (2008) 101–116.

[24] R.G. Mynark, D.M. Koceja, Down training of the elderly soleus H reflex with the use of a spinally induced balance perturbation, J. Appl. Physiol. 931 (2002) 127–133.

[25] G. Pelliccioni, V. Piloni, D. Sabbatini, P. Fioravanti, O. Scarpino, Sex differences in pudendal somatosensory evoked potentials, Technol. Coloproctol. 186 (2014) 565–569.

[26] G. Olchowik, M. Tomaszewski, P. Olejarz, J. Warchoł, M. Różańska-Boczula, R. Maciejewski, The human balance system and gender, Acta Bioeng. Biomech. 171 (2015) 69.

IV

EFFECTS OF WEARING KNEE LENGTH SOCKS ON PERCEPTUAL REGULATION OF ACTION IN COMMUNITY-DWELLING OLDER ADULTS

by

Woo, M. T., Davids, K., Chow, J. Y., & Jaakkola, T

Submitted for publication

Request a copy from the author.