

**IMPACT OF FATIGUE ON LOWER LIMB MOVEMENT CONTROL DURING  
PERTURBED BALANCE IN YOUTH ALPINE SKIERS**

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### **Abstract**

Muscular fatigue is known to induce biomechanical alterations that can increase the risk of different kind of injuries. These alterations may extend beyond the lower limbs and involve changes in knee and pelvis kinematics, potentially contributing to sport injuries like anterior cruciate ligament (ACL) injury. This study aimed to investigate the influence of fatigue on lower limb motor control in youth alpine skiers using a perturbed postural balance method. The primary objectives were to assess the effects of fatigue on knee alignment (knee valgus) and hip kinematics (hip flexion and hip abduction) during postural balance tasks.

A total of fourteen healthy national-level alpine skiers, consisting of 11 men and 3 women, with an average age of  $17.4 \pm 1.8$  years, height of  $176.4 \pm 9.5$  cm, and weight of  $68.4 \pm 14.1$  kg, were recruited for this study. Participants were selected from the local alpine ski gymnasium and the local ski club in collaboration with the Kuopio Region Sports Academy. The measurements were conducted using an instrumented treadmill and a reflective marker-based 3D motion capture system. The protocol involved 10 perturbations with varying directions (anterior-posterior, medial-lateral, lateral-medial) and speeds (slow or fast), randomized at intervals. Perturbed balance tests were conducted before and after a fatigue protocol. The measurements were performed with ski boots on. Statistical analysis revealed no significant differences in knee alignment, hip flexion, or hip abduction between the pre-test and post-test measurements. These findings contradicted the initial hypothesis, as we suggested that fatigue did not significantly affect lower limb motor control by using perturbed postural balance. However, it is important to note that the perturbed balance test demonstrated good usability in assessing postural control in multiple directions.

This study provides valuable insights into the relationship between fatigue and motor control in alpine skiing and contributes to the existing literature on postural balance and athletic performance. Further research is needed to explore additional factors that may influence lower limb motor control and to gain a deeper understanding of the complex interactions between fatigue, postural balance, and sport-specific performance in alpine skiing.

Keywords: Motor control, perturbed postural balance, neuromuscular fatigue, knee valgus, pelvis tilt, pelvis drop

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## **Tiivistelmä**

Tämän tutkimuksen tarkoituksena oli tutkia väsymyksen vaikutusta alaraajojen motoriseen kontrolliin nuorilla alppihiihtäjillä käyttäen aiheutetun tasapainohäiriön testimenetelmää. Pääasiallisena tavoitteena oli arvioida väsymyksen vaikutuksia alaraajojen linjaukseen, erityisesti polven (polven valgus) ja lonkan kinematiikkaan (lonkan koukistus ja lonkan abduktio) tasapainotehtävissä.

Tutkimukseen rekrytoitiin yhteensä neljätoista tervettä kansallisen tason alppihiihtäjää, joista 11 oli miehiä ja 3 naisia, keski-ikä ollessa  $17,4 \pm 1,8$  vuotta, pituuden  $176,4 \pm 9,5$  cm ja painon  $68,4 \pm 14,1$  kg. Osallistujat valittiin paikallisesta alppihiihtolukiosta ja paikallisesta hiihtoseurasta yhteistyössä Kuopion seudun urheiluakatemiaan kanssa. Mittaukset suoritettiin instrumentoidulla juoksumatolla ja osallistujille asetettiin heijastavat markerit 3D-liikkeenanalyysin perustuvaa biomekaanista mallinnusta varten. Mittausprotokolla sisälsi 10 satunnaista häiriötä eri suuntiin (taakse, keskelle, sivulle) ja kahdella eri nopeudella (hidas tai nopea). Mittaukset tehtiin laskettelumonot jalassa ennen ja jälkeen väsymysprotokollan.

Tilastollinen analyysi ei paljastanut merkittäviä eroja polven linjauksessa, lonkan koukistuksessa tai lonkan abduktiossa ennen ja jälkeen väsymysvaiheen. Nämä tulokset eivät vastaa alkuperäistä hypoteesia, sillä tulokset osoittavat, että väsymyksellä ei ollut merkittävää vaikutusta alaraajojen motoriseen kontrolliin käytettäessä häiriköityä tasapainotestimenetelmää. On kuitenkin tärkeää huomata, että häiriköity tasapainotesti osoittautui hyväksi menetelmäksi arvioida asennon hallintaa ja tasapainoa eri häiriösuunnat huomioon ottaen.

Tämä tutkimus tarjoaa arvokasta lisätietoa väsymyksen ja motorisen hallinnan välisestä suhteesta alppihiihdossa ja edistää olemassa olevaa kirjallisuutta asennon ja tasapainon hallinnasta sekä urheilullisesta suorituskyvystä. Yhteenvetona voidaan kuitenkin todeta, että tarvitaan lisätutkimusta selvittämään alaraajojen motoriikkaan vaikuttavista tekijöistä.

Avainsanat: Motorinen kontrolli, tasapainon häiriö (perturbaatio), lihasväsymys, polven medialisaatio/abduktio, lonkan fleksio, lonkan abduktio

**Used abbreviations.**

GTO	The Golgi tendon organ
ACL	Anterior cruciate ligament
MCL	Medial collateral ligament
HUMEA	Human Measurement and Analysis
CGM2	Gait model 2
RPE	Rated Perceived Exertion scale
CNS	Central nervous system
DKV	Dynamic knee valgus
EMG	Electromyography
TMS	Transcranial magnetic stimulation

*With love to my wife Hanna, and to my two lovely daughters Oona and Aada!*

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## 1 INTRODUCTION

Motor control plays a critical role in executing precise movements and maintaining postural stability during alpine skiing. The ability to control lower limb alignment is essential for optimal performance and injury prevention in this demanding sport, and other sports as well (Hrysomallis, 2007). However, neuromuscular fatigue can significantly affect motor control and potentially compromise lower limb alignment, leading to an increased risk of injuries (Bedo et al., 2022).

Neuromuscular fatigue, resulting from prolonged or intense physical activity, can impair the coordination and activation of muscles involved in motor control (Aquino et al., 2022). This fatigue-induced alteration in neuromuscular function can impact the control of lower limb alignment, potentially leading to biomechanical deviations such as knee valgus (medialization of the knee joint) and pelvis drop during alpine skiing.

Perturbed postural balance tests (Lesch et al., 2021) can provide valuable insights into the neuromuscular mechanisms underlying motor control and lower limb alignment. These tests involve introducing controlled disturbances to the body's equilibrium, simulating the challenging and unpredictable conditions encountered during alpine skiing. By examining kinematic parameters of the lower limb alignment during perturbed postural balance tasks in unfatigued and fatigued conditions, we can assess the effects of neuromuscular fatigue on motor control and the associated risks to lower limb instability.

Understanding the influence of neuromuscular fatigue on lower limb alignment during perturbed postural balance tasks is crucial for injury prevention and performance optimization in alpine skiing (Bedo et al., 2022; Koller et al., 2015). By investigating the specific changes in lower limb alignment, such as knee valgus, under fatigued conditions, we can identify potential risk factors and develop targeted interventions to mitigate injury risk.

The aim of this study is to investigate the effects of neuromuscular fatigue on lower limb alignment during perturbed postural balance tasks in alpine skiing. By analyzing the motor control strategies and lower limb alignment patterns under unfatigued and fatigued conditions, we can enhance our understanding of the impact of fatigue on motor control in this specific sport context.

## 2 CONTROL OF MOVEMENT

The control of movement refers to the process by which the nervous system coordinates and regulates the execution of voluntary movements. It involves the integration of sensory information, motor planning, and the activation of muscles to produce purposeful and coordinated actions. The control of movement is a complex process that requires the interaction of various brain regions, spinal cord circuits, and peripheral nerves.

### 2.1 Movement Control

Human beings are inherently designed for movement, enabling us to navigate from one place to another. Understanding the mechanics of this movement requires a foundational knowledge of the structures involved. The human body comprises more than 200 bones, 600 muscles (Rytkönen T, 2020, 22-23), and 900 ligaments, which collectively form our anatomical framework and provide the basis for functionality (Kauranen Kai & Nurkka Niina, 2014, 34-51, 112). It is well-established that the generation and control of movement rely on structures capable of contracting and producing force (Kerr & Rowe, 2019, 187-203). Thus, movement plays a critical role in our daily activities, including walking, running, and even basic functions such as feeding (Shumway-Cook & Woollacott, 2012, 3-7).

Movement control can be defined as **the ability of the nervous system to regulate muscle contractions and execute specific patterns of motion**. This process considers various factors, including the individual, the task, and the surrounding environment. Movement control involves multiple stages, such as intent, planning, programming, and execution of the movement (Magill Richard & Anderson David, 2014, 85-90; Shumway-Cook & Woollacott, 2012, 3-7). Movement itself entails a transition from one position to another, which is a fundamental requirement for mobility and locomotion (Enoka, 2008, 5). Another perspective views movement patterns as complex actions influenced by specific tasks and environmental factors. However, a significant challenge lies in explaining how the nervous system generates these optimal movement patterns (Le Mouel, 2018, 12).



## **2.2 Motor Control**

Motor control and movement control are often used interchangeably, as they refer to similar concepts. In the field of neuroscience, theories of motor control encompass the role of the nervous system in regulating and coordinating movement (Le Mouel, 2018, 12-13). Motor control can be defined as **the capacity to govern the mechanisms of movement, involving the coordination of the nervous system, reflexes, and direct muscle actions.** Specifically, it explores how sensory information facilitates appropriate movements (Shumway-Cook & Woollacott, 2012, 3-7). Human locomotion is a complex function that requires effective coordination between the central and peripheral nervous systems (Grooms et al., 2019). The entire nervous system, in conjunction with muscles, utilizes sensory information to anticipate, refine, and execute desired movements (Kerr & Rowe, 2019, 187-203).

To maintain consistency and avoid conflicting terminology in this study, the term "Motor Control" is used to encompass the complex and diverse aspects of human movement.

### **3 MOTOR CONTROL THEORIES**

In recent years, several theories of motor control have emerged, each aiming to elucidate how movement is regulated by the brain. These theories address variations in perspectives regarding the significance of different neural components involved in movement control. Some theories place emphasis on peripheral influences, while others highlight central stimuli, and yet others underline the role of the environment in governing behavior (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 7-8). In the following sections, the summary of the most pertinent theories of motor control are provided.

#### **3.1 Reflex theory**

In the early 1900s, neurophysiologist Sir Charles Sherrington laid the principle for the Reflex theory, which can be considered the original theory of motor control. According to this theory, the initiation of movement is triggered by a stimulus that activates the muscles through the nervous system, coordinating their actions and resulting in movement. The Reflex theory posits that motor control is primarily achieved through the complex interplay of individual reflexes, which combine to produce complex behaviors. However, this theory has encountered significant limitations. (Shumway-Cook & Woollacott, 2012, 8-9)

One of the key drawbacks of the Reflex theory is its inability to account for spontaneous and voluntary movements. It fails to explain how movements can occur without any external sensory stimulus. For instance, animals can exhibit coordinated movements even in the absence of sensory input. Furthermore, the theory falls through in explaining the occurrence of "prompt" movements that unfold rapidly and do not allow sufficient time for sensory feedback to guide subsequent actions. Lastly, the Reflex theory fails to address the generation of novel and unpracticed movements. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 8-9)

These limitations have prompted the development of alternative theories of motor control that seek to address these gaps and provide a more comprehensive understanding of movement control. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 8-9)

#### **3.2 Hierarchical theory**

Numerous researchers have proposed the notion that the nervous system is organized hierarchically. One of the early proponents of this hierarchical theory was the English physician H. Jackson, who suggested that the brain's structure is a complex system with

distinct levels of control: higher, middle, and lower. Subsequently, this concept garnered support from other researchers and came to be known as the hierarchical organization of motor control. According to this theory, motor control is arranged in hierarchical levels, with higher association areas preceding the motor cortex, which in turn precedes the spinal cord levels of motor function. (Shumway-Cook & Woollacott, 2012, 9-11)

Different researchers have contributed their own enhancements to the hierarchical theory. In the 1920s, Rudolf Magnus, for instance, proposed that reflexes are integral to motor control and that higher centers act as controllers by inhibiting these lower reflex centers. Several decades later, Arnold Gesell and Myrtle McGraw built upon the prevailing scientific understanding of reflex hierarchies in motor control. They emphasized that the development of fine motor control is associated with the increasing corticalization of the central nervous system, underscoring the significance of higher levels of control surpassing lower-level reflexes. This concept of neuromaturation theory plays a significant role within the hierarchical theory and highlights the importance of central nervous system function in motor control. (Shumway-Cook & Woollacott, 2012, 9-11)

However, the reflex/hierarchical theory is not without limitations. It fails to explain the predominance of reflex behavior in specific situations among normal adults. Additionally, individuals exhibit variations in their developmental patterns, and this theory may not adequately account for these individual differences. These limitations warrant further exploration and the development of alternative perspectives. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 9-11)

### **3.3 Motor programming theory**

The motor programming theory emphasizes that a specific motor response can be generated either by a sensory stimulus or through a central process in the absence of an afferent stimulus or external impulse. According to this theory, movement can be executed without dependency on reflex actions, and the spinal network can produce locomotor rhythms even without sensory stimuli or descending patterns from the brain, thereby eliminating the need for feedback. This concept has led to the development of the notion of central pattern generators, which serve as the motor control center within the spinal cord. Some researchers have also proposed that certain specialized actions, such as writing skills, are stored in higher levels of the central nervous system and can be executed automatically. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 11-12)

Like other theories of motor control, the motor programming theory has its own limitations. It does not fully account for the fact that the nervous system must interact with both musculoskeletal and environmental variables to accomplish movement. The central motor program alone cannot solely govern motor actions. Instead, it is important to recognize that this concept was intended to broaden our understanding of the role of the nervous system in motor control and movement regulation. (Shumway-Cook & Woollacott, 2012, 11-12)

Further research is necessary to explore and refine our understanding of the intricate interactions between the nervous system, musculoskeletal system, and environmental factors in motor control. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 11-12)

### **3.4 Systems theory**

The systems theory of motor control is based on the notion that understanding the neural control of movement necessitates knowledge about the characteristics of the system involved and the internal and external forces acting on the body. According to this theory, movement is not controlled solely by central or peripheral mechanisms, but rather through the interaction of multiple systems. Nikolai Bernstein is considered the father of this theory. He conceptualized the body and movement as a mechanical system with numerous degrees of freedom that require coordination. In this view, higher levels of the nervous system guide lower levels, while lower levels coordinate muscle synergies programmed to work together as a unit. As task demands increase, motor control adapts to meet the requirements. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 11-12)

Bernstein's theory of degrees of freedom and synergies has since been expanded upon by other scientists. While the fundamental principles remain, researchers like Latash & Anson, (2006) have proposed that synergies are not solely used by the nervous system to reduce redundant degrees of freedom, but also to ensure flexible and stable motor task performance. The dynamic system theory suggests that individual systems can come together and behave collectively in an organized manner, without the need for higher-level commands to initiate movement. Additionally, this theory emphasizes the significance of movement variability. Optimal motor function requires a certain level of variability, which provides flexibility, adaptability, and the ability to adjust to environmental changes during normal motor control. (Shumway-Cook & Woollacott, 2012, 11-12)

It is important to note that the systems theory highlights the complexity of motor control, with interactions between various systems contributing to movement coordination. Variability in motor control is seen as a necessary and advantageous aspect, enabling adaptability and successful performance in different contexts. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 12-16)

In addition, Bernstein thought that body and movement was acting like a mechanical system, and it has many degrees of freedom to be controlled. Additionally, he emphasizes the importance of coordination of movement. Thus, the higher levels of the nervous system lead the lower levels, and lower levels navigate the muscles. (Shumway-Cook & Woollacott, 2012, 11-12)

### **3.5 Ecological theory**

In the 1960s, physiologist James Gibson proposed a novel perspective on how our motor systems interact with the environment. His research focused on the detection of crucial environmental information and its utilization for movement control. This line of investigation gained support from other scientists and became known as the ecological theory of motor control, establishing its place among the classical motor control theories. While this theory expanded our understanding of the nervous system's role in perceiving and acting within the environment, it does have a notable limitation. It places less emphasis on the organization and internal function of the nervous system itself in facilitating this interaction with external stimuli. (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 16-17)

### **3.6 Summary of motor control theories**

In order to comprehensively understand human motor control, it is essential to consider the different theories of motor control and how they provide distinct perspectives on movement control. These theories highlight various neural components involved in movement (Cano-de-la-Cuerda et al., 2015; Shumway-Cook & Woollacott, 2012, 7-20). The variations among these theories stem from differing philosophical viewpoints regarding the significance of different brain and neural components, such as peripheral versus central influences or the role of environmental information in behavior control (Shumway-Cook & Woollacott, 2012, 7-20).

Determining the best theory of motor control is a challenging task as each theory has its own proponents. Over time, scientists have modified and expanded upon these classical theories to better align with their specific purposes. In many cases, the core elements of classical motor

control theories have remained intact, while incorporating new critical insights. It is important to emphasize that the most comprehensive theory of motor control integrates elements from all existing theories. Such a theoretical framework is necessary to grasp the execution of motor control and movement, as well as the involvement of sensory and motor systems.

## 4 PHYSIOLOGY OF MOTOR CONTROL

Human motor control is a highly complex system that involves the integration and coordination of multiple brain structures, including the primary motor cortex, premotor cortex, supplementary motor cortex, basal ganglia, thalamus, cerebellum, brainstem, and spinal cord. In voluntary movements, commands originate from cortical areas in the brain, with the central nervous system serving as the command center for action (Magill Richard & Anderson David, 2014, 71-78). These executive signals, derived from the movement plan, travel through corticospinal pathways, passing through the brainstem and spinal cord, ultimately reaching motor units in the muscles. Sensory receptors continuously monitor and adjust the desired outcome of the movement (Kerr & Rowe, 2019, 187-203).

Moreover, motor control and movement involve various cortical areas that encompass volition, emotion, and the integration of feed-forward and feedback sensory information. These cortical areas work together to generate a motor plan, exerting descending control over the basal ganglia, hypothalamus, cerebellum, brainstem, and spinal cord via the corticoreticulospinal pathway (Takakusaki, 2017). It is crucial to recognize that signal integration occurs at every level, from the spinal cord to the cerebral cortex (Figure 1).

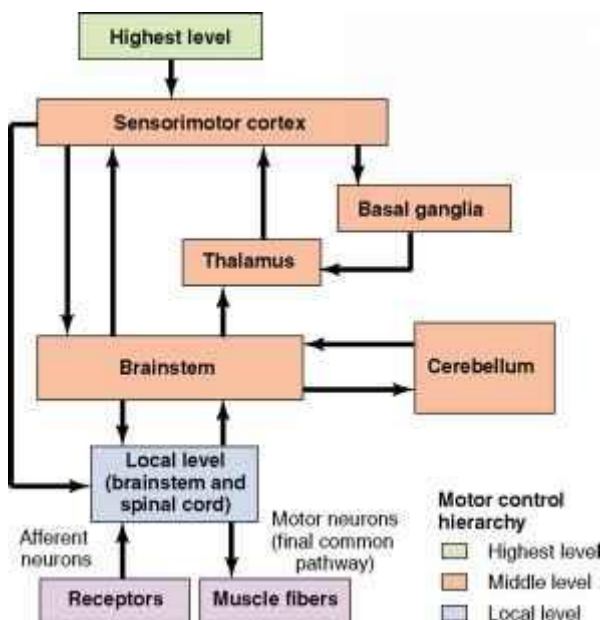


Figure 1. Hierarchical organization levels of neural systems (Magill & Andersson, 2014)

#### **4.1 Structures involved in motor impulse**

Every action necessitates the transmission of signal inputs encompassing the motor plan, intended movement, and feedback corrections. This complicated process occurs swiftly and relies on the coordinated efforts of multiple brain regions and neural pathways. The conventional perspective of this process is often illustrated in a hierarchical manner, with signals propagating from higher brain areas to the spinal cord and subsequently to the muscles. However, it is important to acknowledge that this process is not strictly linear, and signal transmission also occurs in parallel fashion. In the following section, overview of the key structures involved in the transmission of motor impulses are provided (Magill Richard & Anderson David, 2014, 71-78).

#### **4.2 Cerebral cortex**

In a hierarchical point of view, the cerebral cortex serves as the highest level of motor control, characterized by gray matter composed of nerve cell bodies (Magill Richard & Anderson David, 2014, 71-78; Shumway-Cook & Woollacott, 2012, 45-51). Several cortical areas, including the primary motor cortex, parietal cortex, and premotor cortex, play crucial roles in target recognition, task coding, and movement programming. The primary motor cortex is particularly important for initiating and coordinating movements, especially those involving fine motor skills. Additionally, it significantly contributes to the control and acquisition of postural control. The parietal areas receive sensory information from muscle and joint receptors, and they also participate in the voluntary movement control in conjunction with other brain regions (Magill Richard & Anderson David, 2014, 71-78). The premotor areas are responsible for specifying actions, planning movements, and transmitting signals to the motor cortex. Moreover, they are involved in the observation and integration of actions performed by others into one's own motor function (Magill Richard & Anderson David, 2014, 71-78). The motor signals generated in the cortex are then transmitted to the brainstem and spinal cord via the corticospinal tract and the corticobulbar tract. It is worth noting that the nervous system is organized not only hierarchically but also in parallel, and there is functional overlap among different structures. This overlap becomes particularly significant in the context of neural injury, as it enables the utilization of alternative pathways (Shumway-Cook & Woollacott, 2012, 45-51).

#### **4.3 Diencephalon**

The diencephalon comprises the thalamus and hypothalamus. The thalamus serves as a relay center for ascending sensory impulses and motor impulses between the spinal cord, brainstem,



and cerebellum, making it a crucial hub for information integration (Shumway-Cook & Woollacott, 2012, 48-49). The role of the thalamus in motor control has led to the concept of motor thalamus function, suggesting its involvement in regulating, modulating, and amplifying information signals (Bosch-Bouju et al., 2013; Schmitt et al., 2017). On the other hand, the hypothalamus has multidimensional functions primarily associated with the regulation of body homeostasis through its interactions with the endocrine system (Magill Richard & Anderson David, 2014, 76). Additionally, the hypothalamus may play a role in memory and learning processes, expanding its functional repertoire (Burdakov & Peleg-Raibstein, 2020).

### **4.3 Cerebellum**

The cerebellum plays a multifaceted role in motor control, integrating signals from the spinal cord and cerebral cortex while closely interacting with the brainstem. It is particularly involved in the coordination of smooth, precise movements, as evidenced by the presence of inaccuracies in movement following cerebellar damage (Magill Richard & Anderson David, 2014, 76). The cerebellum contributes to movement planning, control, and feedback. Notably, it is believed to actively influence movement timing and sensory acquisition. A key function is to adjust motor responses by comparing the intended movement with the actual movement through sensory inputs, allowing for the modification or refinement of the executed movement. Additionally, the cerebellum plays a significant role in motor learning processes (Manto et al., 2012; Shumway-Cook & Woollacott, 2012, 48).

### **4.4 Brainstem**

The brainstem encompasses several integral regions involved in motor control. The pons, closely connected to the cerebral cortex and cerebellum, serves as a station for various significant neural pathways. In addition to its role in critical bodily functions such as swallowing and breathing, the pons contributes to postural balance control (Magill Richard & Anderson David, 2014, 76-77). The medulla oblongata plays an essential role in voluntary movement by facilitating the crossing of corticospinal tracts at the body midline, enabling their continued path to the cerebellum and cerebral cortex. Another essential area involved in motor control is the reticular formation, which integrates sensory and motor neural impulses by modulating the activity of skeletal muscles through inhibition or excitation (Magill Richard & Anderson David, 2014, 76-77). Furthermore, several nuclei such as the vestibular nuclei, red nucleus, and reticular nuclei are of significance in postural control and locomotion, contributing to various crucial motor control functions (Noga et al., 2020).

The brainstem also serves as a relay station for ascending and descending pathways, transmitting sensory and motor inputs to other regions of the central nervous system. In the context of motor control, the brainstem generates impulses related to initiation, speed, termination, and change of direction in movement. Consequently, it plays a pivotal role in human motor control (Leiras et al., 2022). Boisgontier et al., (2017) emphasized the importance of the brainstem in postural stability, as reduced brainstem volume was associated with impaired postural control and balance.

#### **4.5 Basal ganglia**

The basal ganglia comprise a cluster of subcortical nuclei, including the caudate, putamen, substantia nigra, and pallidus, which contributes to various essential functions, such as the control of voluntary movement and muscle tone. In the region of motor control, its primary function lies in modulating the activities of the motor and premotor cortical areas, acting as a controller to facilitate smooth execution of voluntary movements. Moreover, the basal ganglia also have an important role in cognitive aspects related to motor control, particularly in the selection of motor actions or behavioral programs (Groenewegen, 2003).

Additionally, the basal ganglia have been recognized as playing a crucial role in motor learning (Lanciego et al., 2012). This brain structure is involved in the acquisition and control of learned motor skills (Dhawale et al., 2021; Lanciego et al., 2012). Furthermore, the basal ganglia contribute to the modification and preparation of movements even before their execution, thus playing a pivotal role in movement planning and control (Groenewegen, 2003). Recent advancements have shed light on the basal ganglia's involvement in integrating and weighting afferent sensory information from visual, vestibular, and proprioceptive sources. Dysfunction in basal ganglia gain control may contribute to an impaired response to postural disturbances (Visser & Bloem, 2005).

#### **4.6 Spinal cord**

The spinal cord, though occupying the lowest level of the perception and action hierarchy, plays a crucial role in the initial reception and processing of somatosensory information, as well as in the control of reflexes and voluntary movements through motor neurons. Thus, the spinal networks assume a fundamental function in motor control. Sensory feedback conveyed through these networks interacts with central motor signals, contributing to the underlying muscle activity of voluntary movements (Nielsen, 2016).

At the spinal cord level, simple reflexes can operate without higher-level commands, independently controlling movement (Shumway-Cook & Woollacott, 2012, 46-47). Certain rhythmical movements can be regulated within the spinal cord through circuits known as central pattern generators. These central programs enable the control of movement by combining a limited number of basic motor programs, rather than individually controlling each potential movement and associated muscles. An example of this complex functionality is walking in a noisy and stimulus rich environment (Kerr & Rowe, 2019, 187-203). These circuits are regulated by various sensory signals and extrapyramidal tract inputs, encompassing actions such as motion initiation, velocity control, and fine-tuning of movement (Purves D et al., 2019, 346-357).

## **5 DESCENDING TRACTS IN MOTOR CONTROL**

The following discussion will provide an overview of the descending tracts within the nervous system. These tracts represent the pathways through which motor signals originating from the brain are transmitted to the lower motor neurons, which subsequently convey these signals to the muscles responsible for generating movement. These descending tracts form a crucial communication network that facilitates the execution of voluntary motor actions and plays a fundamental role in motor control.

### **5.1 Corticospinal tract**

The corticospinal tract represents a critical pathway involved in the control of spinal cord activity by the cerebral cortex. As the principal motor pathway for voluntary movement, it originates primarily from the primary motor cortex and sensory cortex regions. Broadly speaking, the primary motor cortex is responsible for executing movements, while the supplementary motor areas contribute to the planning and coordination of intrinsic movement. Additionally, the premotor cortex is involved in planning and coordinating visually guided movement, and the somatosensory cortex facilitates the descending control of somatosensory afferent inputs (Jang & Yeo, 2014; Purves et al., 2004, 393-404; Welniarz et al., 2017).

The signals generated in the neocortex traverse through the internal capsule and cerebral peduncles, eventually reaching the brainstem. Within the caudal region of the medulla, the corticospinal tract undergoes into two branches. The lateral corticospinal tract crosses the midline at the pyramidal decussation before continuing its course toward the contralateral spinal cord. On the other hand, the anterior corticospinal tract remains ipsilateral and descends directly into the spinal cord. Once in the spinal cord, the corticospinal tract terminates in the ventral horn, where it establishes connections with lower motor neurons. These lower motor neurons, in turn, project their axons to the muscles, enabling the execution of voluntary movements (Jang & Yeo, 2014; Purves et al., 2004, 393-404; Welniarz et al., 2017).

### **5.2 Reticulospinal tract**

The reticulospinal tract serves as another prominent descending pathway within the spinal cord. Originating from the reticular formation, this tract consists of multiple fiber bundles. It can be further classified into two distinct components: the medial reticulospinal tract and the lateral reticulospinal tract (Atkinson et al., 2022; Baker, 2011).

The medial reticulospinal tract primarily facilitates voluntary movements and contributes to the enhancement of muscle tone. Conversely, the lateral reticulospinal tract exhibits opposing effects. Both tracts descend bilaterally through the spinal cord, establishing connections with motoneurons that innervate muscles on the same side (ipsilateral) and establishing connections with motoneurons that receive inputs from muscles on the opposite, the contralateral side (Atkinson et al., 2022).

The intricate and diverse connections of the reticulospinal tract allow it to innervate multiple motor unit pools, enabling the coordinated activation of various muscle groups. This structural complexity underscores the crucial role of the reticulospinal tract in tasks such as postural control and locomotion. Studies, including the work by Atkinson et al. (2022), have contributed to our understanding of the functional significance of the reticulospinal tract.

### **5.3 Corticobulbar tract**

The corticobulbar tracts encompass the upper motor neurons that innervate the cranial nerves responsible for controlling the muscles of the face, head, and neck, thereby influencing motor control in these regions. Originating from the motor cortex, these tracts establish direct connections with the nuclei associated with the cranial nerves. Similar to the corticospinal tract, the majority of the axons within the corticobulbar tracts exhibit bilateral innervation, supplying motor neurons on both sides of the body. The intricate interplay between the corticobulbar tracts and the cranial nerves contributes to the precise coordination and execution of motor functions involving facial expressions, mastication, speech, and other movements of the head and neck (Purves D et al., 2019, 402-404).

### **5.4 Extrapramidal tract**

A total of four extrapyramidal tracts contribute to the regulation of involuntary movement, muscle tone, balance, posture, and locomotion. These tracts originate from the brainstem and extend to the spinal cord. Alongside the reticulospinal tract mentioned earlier, the remaining tracts consist of the vestibulospinal tract, rubrospinal tract, and tectospinal tract (de Oliveira-Souza, 2012).

The vestibulospinal tract plays a significant role in human movement control and can be further divided into medial and lateral components. Originating from the vestibular nuclei, these tracts are crucial for the control of balance and posture (de Oliveira-Souza, 2012).

Similarly, the rubrospinal tract shares functional similarities with the corticospinal tract mentioned previously, but it exhibits preferential activity during the execution of automated movements (Olivares-Moreno et al., 2021).

## 6 OVERVIEW OF SENSORY AND AFFERENT RECEPTORS

The central nervous system plays a critical role in the control of movement, and feedback is essential for optimal motor function, ensuring the successful completion of tasks (Kistemaker et al., 2013). In humans, sensory feedback originates from three distinct systems: visual, vestibular, and proprioceptive. These sensory receptors transmit crucial information to all levels of the motor control system, including the cerebral cortex. In this context, an overview of the primary proprioceptive receptors that are most relevant in movement control is provided.

### 6.1 The Muscle Spindle

Muscle spindles are specialized sensory organs that play a unique role in monitoring muscle length, tension, and the rate of changes in length and tension. The human body contains approximately 50,000 muscle spindles, which are composed of specialized muscle fibers known as intrafusal fibers. The response of muscle spindles can be categorized as either static or dynamic, and they are sensitive to progressive stretch. These responses are mediated by gamma motor neurons. As the muscle spindle shortens, its firing rate decreases, returning to the original level once the spindle length stops increasing. In healthy muscles, the muscle spindle exhibits high sensitivity to changes in muscle composition (Kerr & Rowe, 2019, 192-201; Kröger & Watkins, 2021).

Muscle spindle mechanoreceptors are essential for perceiving limb position and movement. These receptors, located within skeletal muscles, consist of encapsulated intrafusal muscle fibers, and are innervated by primary (group Ia) and secondary (group II) proprioceptive sensory neurons. Both types of afferents respond to stretching of intrafusal fibers, with changes in limb position leading to altered firing rates. These receptors are regulated by central nervous system-directed efferent motor control through dynamic and static gamma motor neurons ( $\gamma$ MN). Additionally, neurons control the gain for group Ia/II afferent discharge frequency by innervating the contractile polar ends of intrafusal muscle fibers. Despite sharing the same sensory end organ, group Ia and group II afferents have distinct intra-spindle innervation patterns, activation thresholds, and conduction velocities. These differences enable them to convey different aspects of muscle stretch. Specifically, while both types of afferents signal changes in static muscle length, the dynamic sensitivity of group Ia afferents allows them to indicate the rate of change in muscle length (Oliver et al., 2021).

The information provided by muscle spindles is essential for motor control and movement coordination. By continuously monitoring muscle length and changes in muscle tension, muscle spindles contribute to the regulation of muscle tone, joint position sense, and the coordination of complex movements (Kröger & Watkins, 2021).

Moreover, the negative feedback from spindle afferents enhances the dynamic stiffness of muscles and optimizes the stabilization of posture and movement. It is hypothesized that the central nervous system utilizes muscle spindle information in a predictive manner to activate muscle work (Kistemaker et al., 2013).

## **6.2 The Golgi Tendon Organ**

The Golgi tendon organ (GTO) is a vital sensory receptor located within the tendons of muscles. It serves as a detector of relative muscle tendon tensions through its Ib afferents. The GTO functions through inhibitory mechanisms and responds to increased tension in the tendons. When a muscle contracts and causes the tendon to become taut, the GTO is activated. As an example, when you're walking uphill, the extensor muscles undergo greater stress. This heightened stress triggers heightened activity in the Golgi tendon organ, consequently leading to increased motor neuron activity in the flexors (Kerr & Rowe, 2019, 194; Mileusnic & Loeb, 2006; Shumway-Cook & Woollacott, 2012, 53-54).

Consequently, the GTO plays a major role in preventing muscle injuries (Kistemaker et al., 2013), and it may act as a protective mechanism for the muscle by preventing excessive force and potential damage. When the tension in the muscle reaches a critical threshold, the GTO inhibits further muscle contraction through a reflex mechanism known as autogenic inhibition (Proske & Gandevia, 2012). There have even been proposals suggesting that the feedback from GTOs may have a role in central pattern generators, which are involved in generating rhythmic motor patterns (Kistemaker et al., 2013).

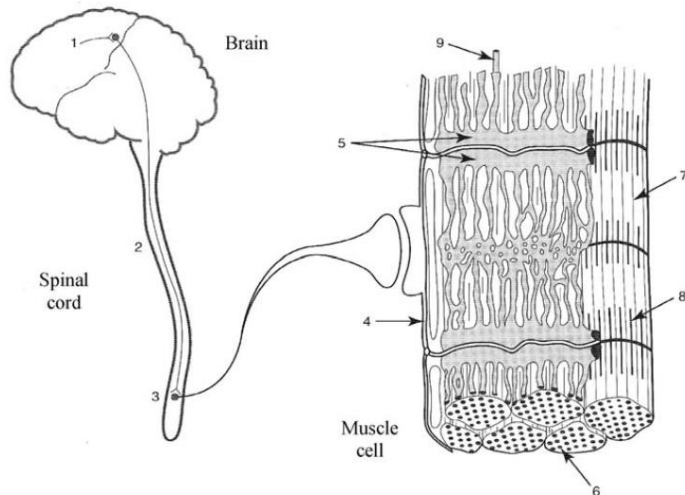


## 7 NEUROMUSCULAR FATIGUE

Fatigue is a complex and multifactorial phenomenon that affects a significant number of individuals (Koral et al., 2020). It is characterized by symptoms such as overwhelming tiredness, energy deficits, and a sense of exhaustion, often associated with the performance of voluntary tasks (Wan et al., 2017). In the context of exercise, fatigue is defined as the inability to sustain the required level of strength. Neuromuscular fatigue, specifically, refers to any exercise-induced reduction in force or power, regardless of the task's sustainability. Essentially, the muscle becomes incapable of performing the required task (Taylor et al., 2016).

From a physiological standpoint, the neuromuscular system attempts to maintain submaximal strength through facilitatory and inhibitory influences, utilizing neural and muscle-related mechanisms to compensate for the decrease in force generation and enhance performance. Several factors contribute to fatigue and impact force generation. Central fatigue involves a decrease in the voluntary activation of the muscle, manifested through changes in the recruitment of motor units, including their number and discharge rates. In other words, fatigue originates from the central nervous system, leading to a reduction in neural drive to the muscles. On the other hand, peripheral fatigue refers to a decrease in the contractile strength of muscle fibers and alterations in the transmission of muscle action potentials, primarily occurring at or distal to the neuromuscular junction (Boyas & Guével, 2011; Koral et al., 2020; Tornero-Aguilera et al., 2022; Wan et al., 2017).

The decrease in force generation associated with fatigue can occur at various "spots" within the neuromuscular system, reflecting the complex nature of this phenomenon. (Figure 2).



Fatigue may be due to alterations in:

1. activation of the primary motor cortex
2. propagation of the command from the CNS to the MN's
3. activation of the motor units and muscles
4. neuromuscular propagation
5. excitation-contraction coupling
6. availability of metabolic substrates
7. state of the intracellular medium
8. performance of the contractile apparatus blood flow

Figure 2. The location of where Muscle fatigue may occur (Boyas & Guevel 2011)

## 7.1 Central fatigue

Central fatigue can be characterized as a reduction in motoneuron excitation resulting from both supraspinal and spinal physiological mechanisms (Figure 3).

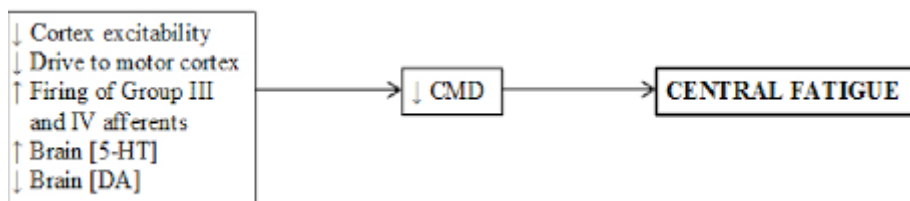


Figure 3. Summary of Central Factors Contributing to Fatigue (Boone et al., 2013).

Typically, central fatigue manifests as a decrease in force generation during low-intensity exercise. In the case of low-intensity exercise, the mechanism behind weaker central command may be attributed to decreased excitation from the motor cortex. However, the

specific causes of supraspinal fatigue remain unclear (Boyas & Guével, 2011). Several assumptions have been proposed, suggesting that supraspinal fatigue may result from exhaustion or the accumulation of neurotransmitters such as serotonin, GABA, and dopamine, which are involved in corticospinal descending excitation. Different neurotransmitters exert either excitatory or inhibitory effects on spinal motoneurons, thereby activating motor units to generate force. Particularly, increased serotonergic activity during prolonged exercise may limit the central command in recruiting motor units. Furthermore, interactions between certain neurotransmitters may also influence central fatigue (Boyas & Guével, 2011; Wan et al., 2017).

Another potential factor contributing to central fatigue is the alteration of certain substances in the brain, such as ammonium ions and glycogen. The accumulation of ammonium ions can decrease motor cortex activity, while a depletion of brain glycogen may also play a role in central fatigue. Additionally, a new assumption relates to humoral signals like cytokines, which are produced by muscle activity. However, the specific role of cytokines in central fatigue remains uncertain and requires further investigation. Notably, one significant mechanism of central fatigue is associated with specific muscle afferents, namely group III and IV muscle afferents, which have the ability to limit cortical activity through supraspinal inhibition (Boyas & Guével, 2011; Wan et al., 2017).

Central fatigue can also occur at the spinal level, and multiple mechanisms may contribute to this phenomenon. Motoneuron activity can be suppressed by inhibitory afferents from intramuscular receptors. The stimulation of group III and IV muscle afferents by factors such as ischemia, hypoxemia, and the extracellular accumulation of potassium and lactate can inhibit alpha motoneuron activity during prolonged fatiguing exercise. Additionally, mechanoreceptors such as muscle spindles and Golgi tendon organs are believed to inhibit neuronal activity via the reciprocal muscle activity. In summary, central fatigue can be influenced by the activation of the primary motor cortex, the transmission of commands from the central nervous system to motoneurons through the pyramidal pathways, and the activation of muscles (Boyas & Guével, 2011).

## **7.2 Peripheral fatigue**

Several factors contribute to peripheral fatigue, including alterations in neuromuscular transmission, muscle action potential propagation, excitation-contraction coupling, and contractile mechanisms (Figure 4). Neuromuscular transmission can be disrupted in various

ways during fatigue when the nerve action potential is converted to a muscle action potential at the neuromuscular junction (Boyas & Guével, 2011; Wan et al., 2017).

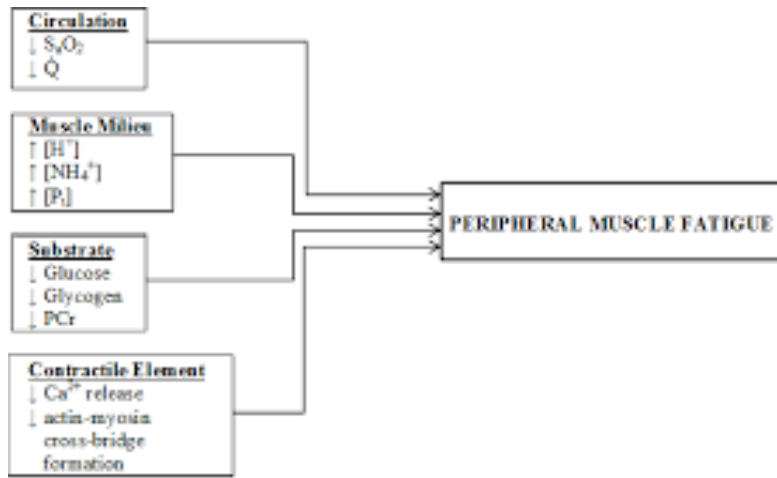


Figure 4. Summary of Peripheral Factors Contributing to Muscle Fatigue Development (Boone et al., 2013).

Insufficient propagation of the nerve potential at the nerve endings, failure of excitation and neurotransmitter secretion in the synaptic cap, neurotransmitter depletion, reduced transmitter release, and decreased sensitivity of post-synaptic acetylcholine receptors and post-synaptic membranes can all contribute to the impairment of this mechanism. Prolonged muscle contraction during fatigue can lead to a decrease in excitability and a subsequent decrease in the amount of transmitter released in the synaptic cap. Intracellular calcium ( $\text{Ca}^{2+}$ ) concentration variations within the nerve ending may play a significant role in this impairment of neuromuscular transmission. Acetylcholine sensitivity of post-synaptic receptors and neuromuscular transmission efficiency are also factors that may influence the impairment of neuromuscular transmission, thereby limiting muscle excitation and force production (Boyas & Guével, 2011; Wan et al., 2017).

In muscle action potentials, the sum of excitatory and inhibitory presynaptic potentials must surpass the muscle cell's excitability threshold.  $\text{Ca}^{2+}$  appears to play the most relevant role in force generation mechanisms (Boyas & Guével, 2011). The neural flow from the brain proceeds to the muscle's transverse tubules, triggering the release of calcium from the sarcoplasmic reticulum into the cytosol and initiating cross-bridge cycling. This process, known as excitation-contraction coupling, involves the opening of ryanodine receptors, leading to the release of  $\text{Ca}^{2+}$  from the adjacent sarcoplasmic reticulum into the sarcoplasm. Binding of  $\text{Ca}^{2+}$  activates troponin and displaces tropomyosin from the myosin-binding site on actin, enabling cross-bridge cycling to occur (Wan et al., 2017).

High-frequency stimulation may lead to the accumulation of potassium ions ( $K^+$ ), which can influence the action potential. Weakened or impaired sodium-potassium ( $Na^+/K^+$ ) pumps can disrupt cellular homeostasis by affecting the concentration of  $Na^+/K^+$  in the cell membrane. This ionic movement can alter the action potential and limit  $Ca^{2+}$  release. ATP concentration is also crucial for normal action potential generation, force production, and muscle relaxation. ATP is required for myosin ATPase and  $Ca^{2+}$  ATPase, which are involved in muscle energy processes. Depletion of glycogen, necessary for ATP production, can lead to fatigue and disturbances in action potentials. Glycogen levels have been shown to affect excitation-contraction coupling and relaxation (Allen et al., 2008; Boyas & Guével, 2011; Wan et al., 2017).

Metabolic factors can also contribute to muscle fatigue. During muscle contraction, blood flow decreases, and prolonged restriction of blood flow can lead to fatigue. Restricted blood flow reduces oxygen supply and results in the accumulation of metabolites, which can impact muscle contraction. Intracellular metabolites such as hydrogen ions ( $H^+$ ), lactate, inorganic phosphate (Pi), and reactive oxygen species (ROS) can influence cross-bridge activity.  $H^+$  accumulation is considered a major contributor to fatigue development. Increased  $H^+$  concentration leads to decreased pH, which affects  $Ca^{2+}$  release from the sarcoplasmic reticulum, the sensitivity of troponin C to  $Ca^{2+}$ , and cross-bridge cycling, ultimately impacting muscle force. Pi concentration can increase during high-intensity exercise and is recognized as a major factor in the development of fatigue. Pi also affects  $Ca^{2+}$  release and signal activation. ROS can induce muscle fatigue through the oxidation of muscle cell proteins, including the  $Na^+-K^+$  pump, myofilaments, and RyR1. ROS inhibits  $Ca^{2+}$  release and  $Ca^{2+}$  sensitivity in muscle myofibrils and may directly inhibit motoneurons through IV muscle afferents (Allen et al., 2008; Boyas & Guével, 2011; Wan et al., 2017).

### **7.3 Potential mechanism for adaptation to fatigue**

During fatiguing exercise, the human body employs various adaptive mechanisms to counteract fatigue and sustain force generation. These adaptive mechanisms play a crucial role in maintaining muscle performance (Figure 5). Firstly, one key mechanism is the increased recruitment of motor units and modulation of their discharge rate, particularly in submaximal exercise. This process involves the activation of additional motor units to compensate for fatigue-induced declines in force production. Additionally, the modulation of motor unit discharge rate contributes to fatigue resistance by optimizing motor unit firing patterns (Allen et al., 2008; Carpentier, 2001).

Another important mechanism is the phenomenon of muscle potentiation, which encompasses several factors that enhance muscle performance. This includes an increase in cortical excitability, as evidenced by motor-evoked potentials, which reflect enhanced excitability of the motor cortex. Furthermore, the performance of repeated or continuous voluntary contractions leads to the generation of additional stimuli, further potentiating muscle activity. Post-activation potentiation, achieved through voluntary muscle contractions, enables greater force production by capitalizing on the residual effects of prior activity. However, this phenomenon is strongly dependent of balance between the level of fatigue and potentiation. Long-term resistance training increases fatigue resistance (Wilson et al., 2013).

Lastly, the concept of "muscle wisdom" can be considered an adaptive mechanism that prevents excessive muscle activity before it becomes detrimental to the body. This refers to the regulation of motor unit firing rates to match the altered force-producing characteristics of a muscle because of fatigue. The precise mechanisms underlying muscle wisdom are not yet fully understood, but it is believed to involve neural feedback mechanisms that regulate muscle activation and force output (Allen et al., 2008).

These adaptive mechanisms contribute to the body's ability to sustain the adequate motor control during the fatigue and maintain the sufficient force generation. Understanding and optimizing these mechanisms through appropriate training and conditioning strategies can enhance fatigue resistance and overall muscular performance.

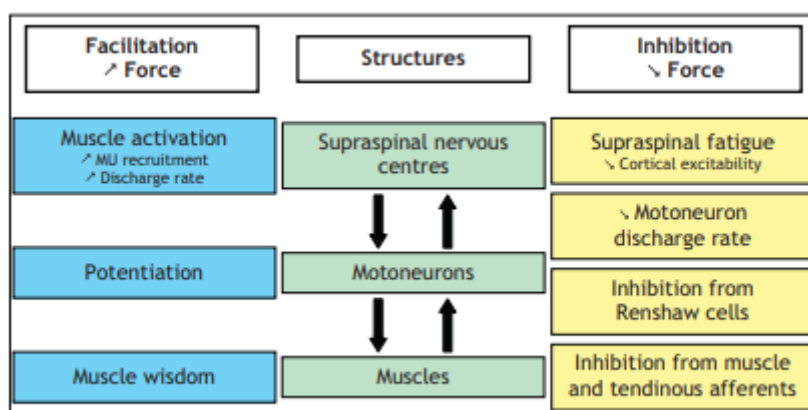


Figure 5. Mechanism influencing the maintenance of muscle force (Boyas & Guevel, 2011)

#### 7.4 Fatigue on lower limb control

Fatigue has been identified as a significant factor contributing to altered postural stability. The impact of fatigue on the neuromuscular system and balance control is evident through various

outcomes, including increased sway path and sway path velocity (Berger et al., 2010; Nardone et al., 1997), greater variability in postural responses, altered activation of spinal reflexes, and impaired coordination of antagonistic muscles during complex postural tasks (Berger et al., 2010; Bisson et al., 2011). Consequently, it is well-established that fatigue has a negative influence on balance control (Koller et al., 2015).

Additionally, fatigue affects lower limb kinematics. Bedo et al. (2022) observed an increase in knee valgus during single-leg tasks and a reduction in knee and hip flexion following a fatigue protocol. Furthermore, fatigue led to increased hip abduction during side-step cutting and single-leg drop landing tasks. Similar findings were reported by Hewett et al., (2005), who observed increased knee valgus movements during jump-landing tests, indicating impaired lower limb alignment control. Benjaminse et al. (2007) highlighted that fatigue can alter landing techniques, leading to reduced knee flexion. Decreased knee flexion is particularly concerning as it is associated with an increased shear force component on the knee, contributing to a higher risk of knee injuries.

Fatigue also exerts its influence on body sway in both the anterior-posterior and medio-lateral directions (Sarabon & Hirsch, 2016). Localized muscle fatigue has been shown to affect dynamic postural stability, as evidenced by a decrease in maximum propulsion force and an increase in center of pressure area following fatigue protocols (Aquino et al., 2022; Salavati et al., 2007). Significant variations were observed in center of pressure displacement in both the anteroposterior and mediolateral directions. These findings suggest that fatigue may impact proprioceptive mechanisms associated with muscle fatigue, such as delayed muscle reaction time or inappropriate efferent muscle responses. Fatigue can also affect mechanoreceptor feedback from ligaments and compromise joint stability (Bedo et al., 2022; Gandevia, 2001). Furthermore, hip abductor/adductor fatigue has been implicated in impaired postural control (Dury et al., 2022; Paillard, 2012). It has been hypothesized that weakened hip abductor strength can shift the control strategy toward the ankle, thus affecting postural balance control. Insufficient hip abduction and external rotation strength, often attributed to gluteus medius dysfunction, can contribute to a decrease in postural control and an increase in knee valgus angle (McMullen et al., 2011). Proprioceptive inputs from the hip play a crucial role in maintaining postural control (Salavati et al., 2007).

In summary, the gluteus medius and gluteus maximus muscles are key contributors to pelvic stability and lower extremity function. These muscles play a vital role in maintaining optimal knee position and preventing dynamic knee valgus (Rinaldi et al., 2022).



## 8. LOWER LIMB CONTROL IN ALPINE SKI

Alpine skiing is recognized as a high-risk sport due to its inherent nature. During a race run, skiers experience substantial forces at high velocities, while assuming lower body postures that may expose them to an increased risk of injury. Additionally, the design and development of ski equipment can influence the skier's risk of injury by affecting the distribution of forces and torques applied onto the knee (Kokmeyer et al., 2012). In a ski race, all three muscle work methods (concentric, eccentric, and isometric) are employed, and these methods change dynamically throughout the race. The combination of high speed and force requirements poses significant challenges to the skier's muscle function and postural control (Kröll & Spörri, 2015). Notably, eccentric muscle work is predominantly utilized during a race run (Alhammoud et al., 2020; Ropret, 2017).

Effective lower limb control is closely associated with optimal dynamic knee alignment, strong hip external rotators, robust core stability, and appropriate activation patterns of thigh muscles. Understanding the importance of maintaining good dynamic knee posture and hip rotator strength can help optimize injury prevention strategies not only in alpine skiing but also in other sports. Alpine ski boots provide external support to the foot-ankle-shank complex, which can positively influence postural control. However, Tchórzewski et al., (2013) found that wearing ski boots resulted in reduced stability, although the extent of reduction depended on the test type, movement plane, and surface conditions. Furthermore, Dury et al. (2022) highlighted that individuals may adopt different neuromuscular and kinetic ankle strategies to control ankle destabilization in response to hip abductor muscle fatigue.

In alpine skiing, adverse leg alignment and excessive dynamic knee valgus are commonly observed, placing additional structural loads on the neuromuscular system. Each leg can experience forces equivalent to twice the skier's body weight, with the knee joint undergoing extreme kinematics involving high degrees of flexion and valgus. As a result of the nature of alpine skiing, skiers are exposed to high vibration loads and impact-like forces, primarily affecting the knee joint and its stabilizing muscles (Ellenberger et al., 2021). These conditions, combined with the ischemic environment and the heightened response of all muscle fibers, contribute to muscle fatigue during alpine skiing. Both peripheral and central factors play a role, and the demands of a race run have significant implications for motor control and performance. Particularly during movements requiring large forces to react to sudden external perturbations, proper sensorimotor abilities are crucial to achieve the

necessary steep inward-leaning angles. Fast reactions to lateral and forward-backward disturbances in balance are also vital for injury prevention (Z. Wang et al., 2022).

Furthermore, in alpine skiing, postural balance is constantly challenged by the skier's upright posture being forced into a knee-bent position due to the ski boots and skis (Koehle et al., n.d.; Z. Wang et al., 2022). The nature of alpine skiing also tests the skier's ability to resist external forces. Both anterior-posterior and medio-lateral balance are challenged depending on the section of the run, with medio-lateral balance being particularly affected and anterior-posterior balance influenced by velocity changes during the run (Lesnik et al., 2017). Hence, it is reasonable to conclude that good postural balance and motor control are essential factors in alpine skiing as well as in other sports in general (Hrysomallis, 2007).

### **8.1 Lower limb injury in alpine ski**

The risk of injury in alpine skiing is remarkably high, with approximately one out of every three skiers experiencing a time-loss injury, resulting in an incidence rate of 9.8 injuries per 1000 runs (Bere et al., 2011). Lower extremity injuries are the most common in alpine skiing (Davey et al., 2019). Among professional skiers, knee injuries, particularly involving the anterior cruciate ligament (ACL), are prevalent (Bere et al., 2011). The medial collateral ligament (MCL) is also frequently injured in the knee. Other common injuries include tibial fractures, partial gastrocnemius tears, ankle sprains, and fractures (Davey et al., 2019). Many injuries occur during turns when skiers lose balance control. If the ski engages with the snow, a mechanism known as valgus-external rotation may occur. This often leads to uncontrolled forward leaning and alignment flaws in the lower limb, resulting in abduction and external rotation of the tibia. Consequently, a valgus force is exerted on the knee, with the ski acting as a lever to maximize torque, forcing the knee into a pronounced valgus position (Bere et al., 2011; Davey et al., 2019; Kokmeyer et al., 2012).

One common cause of ACL injury is the phantom foot mechanism, which occurs when the skier is out of posterior balance, and the weight is concentrated on the inside edge of the ski tail, causing internal rotation of the downhill knee. In this position, the hips are positioned below the knees, and the upper body faces downhill (Davey et al., 2019). Another significant injury mechanism for ACL injury is the boot-induced mechanism. This occurs when the skier loses postural balance control posteriorly during a jump and landing with an extended, stiff knee. In this injury mechanism, the stiff boot drives the tibia away from the femur (Davey et al., 2019).

Additionally, the slip-catch mechanism may lead to unfavorable outcome characterized by internal rotation and valgus of the knee. In the slip-catch mechanism, the ski inside edge unexpectedly catches the snow surface, exerting a force that causes the knee to undergo internal rotation and valgus positioning (Bere et al., 2011).

In summary, poor balance control is a major factor associated with an increased risk of injuries (Hrysomallis, 2007). Muscular fatigue is known to impair movement control through both motor and sensory dimensions. Disturbances in the motor dimension can result from a reduced capacity to generate force due to motor unit discharge cessation or reduced discharge rate of active motor units. In the sensory dimension, muscular fatigue may impair the signal pathway to the central nervous system, potentially through the inhibition of motoneuron pools, presynaptic inhibition of 1a afferents, and modulation of the supraspinal descending drive. Furthermore, metabolites resulting from muscular fatigue can interfere with the transmission of proprioceptive afference from muscle spindles to the central nervous system (Rinaldin et al., 2021).

## 9 HYPOTHESIS AND THE PURPOSE OF THE STUDY

The influence of fatigue on lower limb motor control is significant. Fatigue can impair movement control through both motor and sensory perception. In the motor perception, fatigue may lead to a decreased capacity to generate force, resulting in reduced motor unit discharge or discharge rate of active motor units. This can affect muscle activation patterns and lead to compromised control of movement. In the sensory sensation, fatigue can disrupt the signal pathway from the muscles to the central nervous system. This may involve inhibition of motoneuron pools, presynaptic inhibition of sensory nerve fibers, and modulation of the descending drive from the brain. Additionally, metabolites produced during fatigue can interfere with the transmission of proprioceptive information from muscle spindles to the central nervous system. These effects of fatigue on lower limb motor control can result in decreased coordination, impaired balance, altered joint kinematics, and increased risk of injury. It is crucial to consider the impact of fatigue on motor control when designing training programs and injury prevention strategies (Boyas & Guével, 2011; Taylor et al., 2017; Wan et al., 2017).

The objective of this study was to assess the impact of fatigue on motor control of the lower limbs, specifically postural balance control, during perturbed postural balance tasks. Postural balance and body control are critical components in alpine skiing, and impaired postural balance control has been associated with a higher risk of lower limb injuries (Hrysomallis, 2007). In the context of alpine skiing, postural balance control is particularly relevant to lower extremity disability, as the loss of balance can subject the knee to forces and torques that predispose it to severe injuries. Video analyses of anterior cruciate ligament injuries occurring in alpine skiing have demonstrated that a significant proportion of these injuries involve a loss of balance control preceding the occurrence of stumbling (Bere et al., 2011).

Furthermore, exhaustive exercise affecting specific muscle groups has been shown to impact postural control when there is a strength loss of at least 25-30% of maximal voluntary contraction (Paillard, 2012; Zemková & Zapletalová, 2022). Fatigue is generally believed to result in increased postural sway and impaired balance following intensive exercise (Zemková & Zapletalová, 2022). Additionally, fatigue may contribute to alterations in the effectiveness of sensory and motor signal functions involved in postural control (Paillard, 2012).

To the best of the authors' knowledge, this study represents the first investigation into the influence of fatigue on lower limb motor control by using perturbed postural balance assessment in youth alpine skiers. The primary research question and corresponding hypotheses for this study are as follows:

Research Question:

**Does fatigue affect lower limb movement control in perturbed balance tasks in young alpine skiers?**

Hypotheses:

**Fatigue impairs movement control resulting more knee medialization, pelvis lateral movement and anterior pelvis tilt in response to the perturbation.**

Fatigue may lead to alterations in postural balance control, particularly affecting the alignment of the lower limbs. Increased knee valgus, as observed by Bedo et al. (2022), may be associated with a greater risk of knee injuries. Furthermore, fatigue may result in altered knee flexion angles, which is a known major risk factor for knee injuries due to increased shear force components and excessive structural load on the neuromuscular system.

Fatigue may affect hip flexion (pelvis tilt) and hip abduction (pelvis drop). Previous studies have highlighted the importance of the strength of the gluteus medius and gluteus maximus in preventing dynamic knee valgus. These muscles are generally considered key factors contributing to pelvic stability and lower extremity function (Rinaldi et al., 2022)

## 10 METHODS

This study was part of a broader research conducted at the University of Eastern Finland related to balance and lower limb movement control in young alpine skiers. The data for this study was collected in the HUMEA (Human Measurement and Analysis) laboratory during the autumn of 2022. Ethical approval was obtained from the local research ethical committee (Pohjois-Savon sairaanhoitopiiri) in compliance with the ethical standards outlined in the Declaration of Helsinki.

### 10.1 Subjects

Seventeen youth national level alpine skiers (11 men, 6 women) with a mean age of  $16.8 \pm 2.1$  years, height of  $173.1 \pm 10.6$  cm, and weight of  $68.4 \pm 14.1$  kg were recruited as participants for this study. The recruitment process involved collaboration with the Kuopio Region Sports Academy, specifically targeting students from the Nilsjä (Tahko) alpine high school and athletes from the local ski club. Inclusion criteria encompassed individuals between the ages of 14 and 20 who were healthy and actively involved in alpine ski racing. Exclusion criteria included the use of medications or the presence of diseases that could affect participation, any acute lower limb injuries, recent lower limb surgeries, or bone fractures within the past year. All participants (and parents of underage participants) received written and verbal instructions, and their informed consent was obtained in writing prior to their participation. It is important to note that participation in the study was completely voluntary, and participants had the right to withdraw from the study at any time. Due to incomplete recovery from flu in three participants, 14 participants (11 men, 3 women) with mean age of  $17.4 \pm 1.8$  years, height  $176.4 \pm 9.5$ cm, and weight  $71.7 \pm 14.1$ kg completed the fatigue protocol and were included in the final analysis.

### 10.2 Measurement protocol

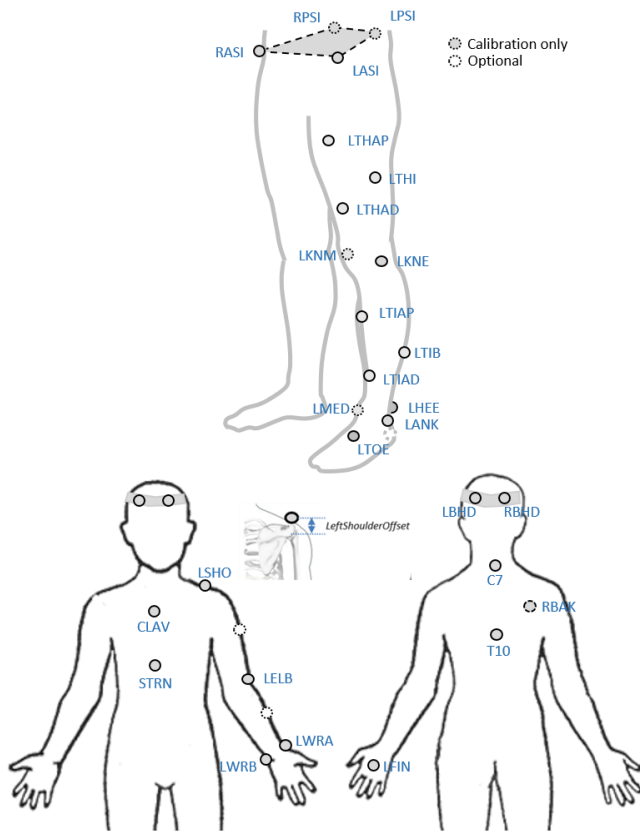
All measurements were conducted at the HUMEA laboratory, located in the Department of Technical Physics (formerly Applied Physics) and Department of Biomedicine, Faculty of Sport, and Exercise Medicine, at the University of Eastern Finland, Kuopio. The laboratory equipment consisted of a 3D motion capture system comprising 10 reflective-marker-based cameras (100 Hz, Vicon Vero, Vicon Motion Systems Ltd., Oxford, United Kingdom) and an instrumented treadmill (1,000 Hz, M-gait, Motek Medical, Houten, The Netherlands) (Figure 6).



Figure 6. Instrumented treadmill (Motek) and the test position in anterior-posterior direction

Kinetic and kinematic data were captured and analyzed following the manufacturer's guidelines. Prior to each measurement session, calibration of the motion capture device was performed using the Vicon T calibration device. During the laboratory measurements, participants were informed about the measurement protocol. Height and weight measurements were taken, along with additional specific measurements required for biomechanical modeling, such as the distance between the left and right anterior superior iliac spine (inter ASIS distance), ankle width, and knee width. These measurements were taken from the participant's dominant leg, which was determined by asking, "With which leg do you kick the ball?"

Before the actual measurements, participants performed an individual warm-up protocol of approximately 10 minutes, including activities such as jogging, mobility exercises, and muscle activation. Following the warm-up, the preparation phase involved attaching reflective markers to the participant's body and ski boots (Figure 7). The open-source biomechanical gait model 2 (CGM2) was used for marker placement, and additional reflective markers were placed on the moving treadmill to capture the participant's movement concurrent with the treadmill belt. The preparation phase also included the setup of wireless EMG, although this data was not utilized in the present study.



CGM2.3 marker set

Figure 7. Used marker set (modified from Peters et al., 2009)

The measurement protocol began with static and dynamic calibrations. During static calibration, participants stood in an erect position, while dynamic calibration involved performing squats, 1-leg squats, and "compass point" reaching tasks. After calibration, the actual measurements commenced with the participant standing on the instrumented treadmill in a one-leg standing position, with the knee flexed, simulating a relaxed skiing posture, and wearing ski boots (Figure 8). Throughout the measurements, participants were instructed to maintain their postural balance as best as possible and to restore their posture to the starting position if balance was disrupted. Foot touches were also recorded.



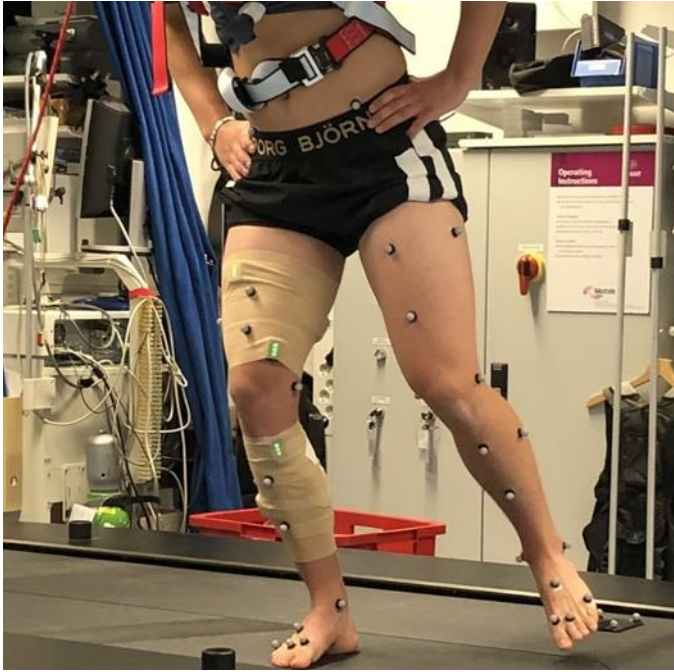


Figure 8. Lateral-medial trial (note that this picture is without the ski boots)

The test protocol consisted of perturbation to the standing balance by a movement of the treadmill. The direction of the movement was known to the participant, but timing randomized with the gap between each perturbation being  $4.5 \pm 0.9$  seconds, which was determined to be sufficient for participants to recover stable balance between perturbations. The test protocol was performed before and after a 90-second box-jump test (part of Alpine Canada Physical Fitness testing) conducted to induce fatigue. Fatigue levels were monitored using the Rated Perceived Exertion (RPE) scale. Each participant, and for pre- and post-fatigue test, the protocol proceeded in the order anterior-posterior, medial-lateral, and lateral-medial perturbation test. The test protocol followed the study conducted by Lesch et al. (2021) and consisted of 10 randomized perturbations. Fast perturbation speed was used for the anterior-posterior perturbations and slow speed for the medial-lateral, and lateral-medial perturbations. The protocol for both test speeds is detailed below. Familiarization with the protocol and the instrumented treadmill had been conducted earlier, following the calibration. In cases of failed execution, the measurement was repeated. Throughout all perturbation trials, a safety harness was used to ensure participant safety.

For fast perturbations (total duration of the protocol 52 s), the target speed was set to 0.25 m/s for 0.5 seconds (belt movement  $\approx 125$  mm), with a maximum acceleration limited to  $4 \text{ m/s}^2$ . The belt was then decelerated to a full stop using the same acceleration. It should be noted that the treadmill could only reach 75% of the programmed  $4 \text{ m/s}^2$  acceleration. For slow perturbations (total duration of the protocol 48s), the treadmill belt was set to move with a maximum acceleration and deceleration of  $0.3 \text{ m/s}^2$ , targeting a belt velocity of 0.15 m/s for 0.5 seconds (belt movement  $\approx 75$  mm).

### **10.3 Data analysis**

The Vicon software was utilized to calculate the 3D trajectories of the reflective markers within the capture volume. Manual marker labeling was performed, and any gaps in the marker data were filled using the Vicon Nexus software. In cases where markers were missing, extrapolation was carried out using MATLAB R2021b (Mathworks Ltd., Massachusetts, United States). The preferred marker set was the CGM2, although the Plug-in Gait model was used due to unresolved analysis issues. The decision to use Plug-in Gait was based on the similarity of marker placement between the two models, with CGM2 having more markers.

The raw marker data underwent filtering with a fourth-order, zero-lag, 6 Hz low-pass Butterworth filter after which kinematic modeling as per Vicon's Plug-in Gait model was performed. Custom-made scripts written in MATLAB R2021b were used for extracting and processing the data, specifically the variables of knee flexion, knee medialization, hip flexion, hip(pelvis) drop and hip rotation.

For data analysis, the mean values of all 10 perturbations in the posterior, lateral, and medial directions were calculated. Any unsuccessful trials involving significant stumbling or foot touch, or cases where the marker paths were inadequate, were excluded from the final analysis.

The kinematic variables in this study were represented in angles ( $^{\circ}$ ). The adduction values which get the negative value state for abduction, while positive values represented adduction angles for knee and hip drop angles (tilt, drop), larger positive values indicated flexion, while negative values indicated extension. In pelvis tilt a positive value represents anterior pelvis tilt, while a negative value indicates posterior pelvis tilt. Pelvis drop refers to the unilateral descent in the frontal plane of the pelvis. Typically, this drop occurs on the side opposite to the weakened or affected side. A positive value represents contralateral pelvis drop, indicating that the other side of the pelvis is elevated. The hip belt represents the relationship between the movement of the treadmill's belt and the participant's pelvis. A negative value indicates minimal movement of the belt relative to the pelvis, while positive value indicates vice versa. Knee distance reflects the alignment of the knee, specifically knee valgus. A positive value indicates medialization of the knee, commonly referred to as knee valgus, whereas a negative value signifies knee varus, which is the opposite of knee valgus.

### **10.4 Statistics**

All the provided data calculations were conducted using MATLAB software. The mean values and standard deviations were computed based on the 10 perturbations. The determination of absolute maximal angles and time to reach maximal values for pelvis tilt, pelvis drop, lower limb alignment (knee distance), and hip lateral movement relation was determined using Excel 2020 (Microsoft Corporation, Washington, US).

The analysis time window was set to begin 0.5 seconds before the perturbation and end 1.5 seconds after. This enables the assessment of both the anticipatory responses and the recovery from perturbations. However, when comparing the means of absolute maximal values and the change values between the pre-test and post-test, the period from the start of the perturbation to 1.5 seconds after was considered.

Statistical analyses were conducted using SPSS Statistic 27 (IBM Corporation, New York, US). The data was assessed for normal distribution using the Shapiro-Wilk test. Based on the normality test results, either paired samples t-tests or nonparametric related samples tests were selected. The statistical significance level was set at  $p < 0.05$ .

## 11 RESULTS

In this study, we utilized tailored perturbed postural balance methods to explore the impact of fatigue on lower limb movement control. We achieved this by measuring postural balance control during perturbations. Fatigue levels were assessed using the Rated Perceived Exertion (RPE) scale (Table 1).

Table 1. The mean values of the fatigue RPE scale (6= very easy, 20= extremely strenuous)

	N	Minumum	Maximum	Mean	Std.Dev
<b>Rpe 6–20</b>	14	14	17	15,64	0,93

The differences in responses to these perturbations were examined by comparing mean values before and after the pre- and post- tests, focusing on pelvis tilt, pelvis drop, hip lateral movement, and lower limb alignment (knee distance).

To explore deeper into the analysis of absolute changes in joint angles, we compared individual participants' maximal pre-test values with their post-test values. Additionally, we measured the correlation between pre-test and post-test results to assess the efficacy of this testing protocol.

### 11.1 Pelvis tilt

Pelvis tilt (Figure 9) indicates the orientation of the pelvis with respect to the ground and is reported as a change from the instant of perturbation. The mean of maximal posterior pelvis tilt during the pre-test was  $-5.87^{\circ} \pm 1.25$ , and during the post-test, it was  $-6.81^{\circ} \pm 1.12$ . The mean difference between the pre-test and post-test was  $0.94^{\circ} \pm 0.94$ , with a p-value of 0.003. The effect size, Cohen's d, was calculated to be 1.09.

In terms of the time to reach maximal pelvis tilt, the mean during the pre-test was  $0.60s \pm 0.02$ , and during the post-test, it was  $0.61s \pm 0.02$ . The mean difference between the pre-test and post-test was  $0.01s \pm 0.94$ , with a p-value of 0.06. The effect size, Cohen's d, was calculated to be -0.60. The significant differences were found in maximal posterior pelvis tilt between pre-test and post-test, otherwise no statistically significant differences were observed.

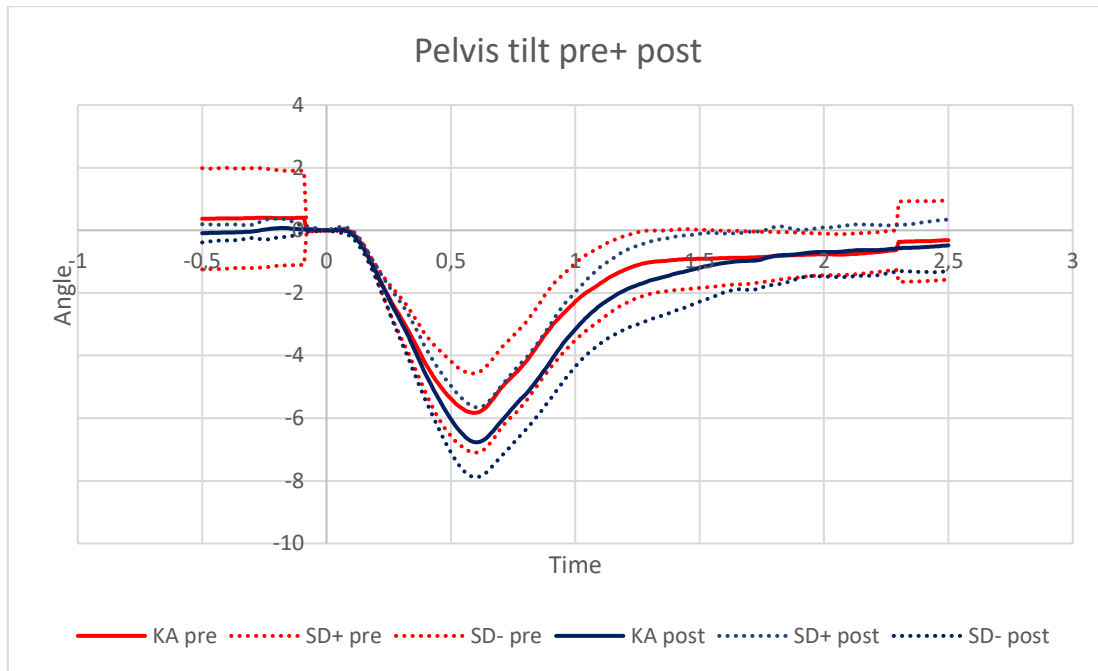


Figure 9. Change in pelvis tilt posterior perturbation condition relative to the instant of perturbation onset.

## 11.2 Pelvis drop

The mean of maximal pelvis drop medial (Figure 10) during the pre-test was  $1.97^{\circ} \pm 4.22$ , and during the post-test, it was  $2.35^{\circ} \pm 2.89$ . The mean difference between the pre-test and post-test was  $-0.38^{\circ} \pm 5.25$ , with a p-value of 0.79. The effect size, Cohen's d, was -0.07.

In terms of the time to reach maximal pelvis drop medial, the mean during the pre-test was  $1.01s \pm 0.22$ , and during the post-test, it was  $1.15s \pm 0.31$ . The mean difference between the pre-test and post-test was  $-0.13s \pm 0.38$ , with a p-value of 0.22. The effect size, Cohen's d, was calculated to be -0.35. The pre-test and post-test values were found to be similar, and no statistically significant differences were observed.

The mean of maximal pelvis drop during lateral (Med-lat) (Figure 11) perturbation in the pre-test was  $-1.44^{\circ} \pm 1.88$ , and during the post-test, it was  $-1.42^{\circ} \pm 1.87$ . The mean difference between the pre-test and post-test was  $-0.02^{\circ} \pm 2.76$ , with a p-value of 0.98. The effect size, Cohen's d, was calculated to be -0.01.

In terms of the time to reach maximal pelvis drop lateral, the mean during the pre-test was  $0.68s \pm 0.04$ , and during the post-test, it was  $0.68s \pm 0.06$ . The mean difference between the pre-test and post-test was  $0.00s \pm 0.05$ , with a p-value of 0.91. The effect size, Cohen's d, was

calculated to be 0.03. The pre-test and post-test values were found to be similar, and no statistically significant differences were observed.

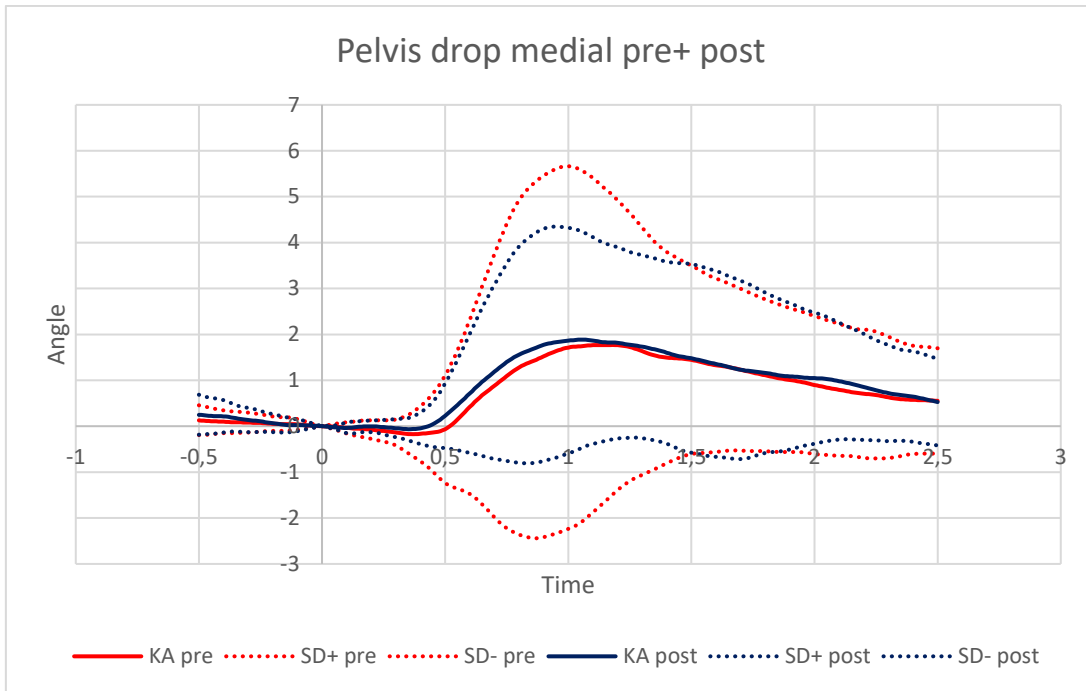


Figure 10. Change in pelvis drop in medial perturbation condition relative to the instant of perturbation onset.

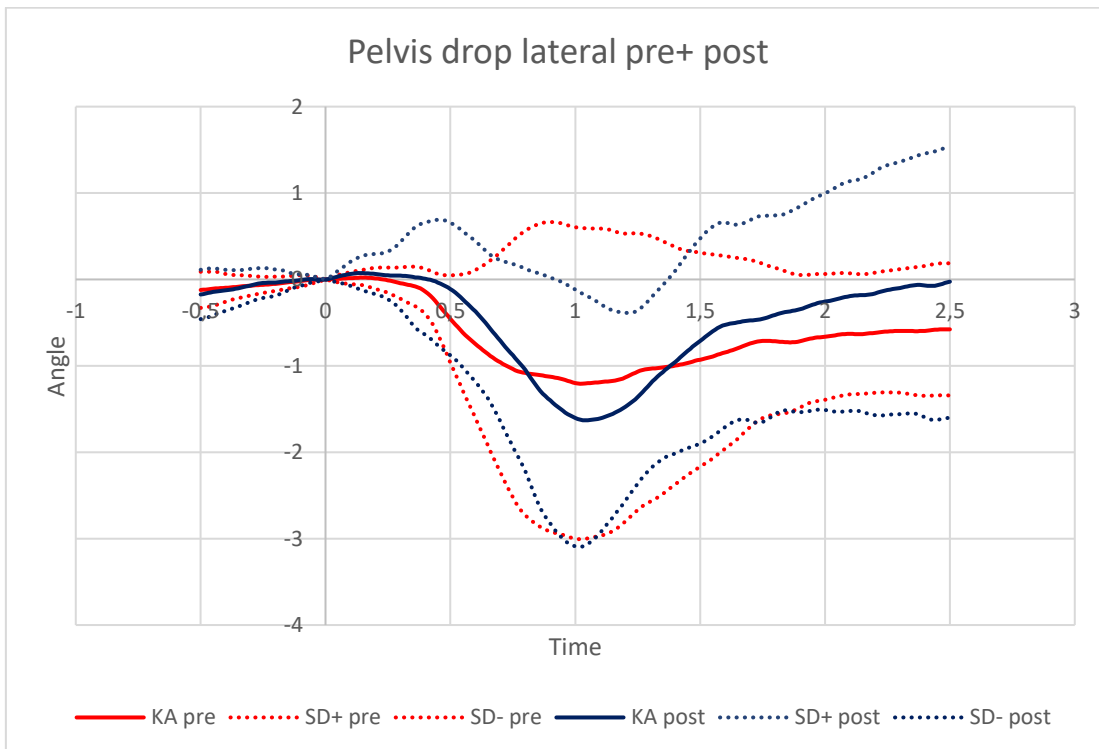


Figure 11. Change in pelvis drop in lateral perturbation condition relative to the instant of perturbation onset.

### 11.3 Hip belt

The mean of maximal hip belt medial (Figure 12) during the pre-test was  $-31.25^{\circ} \pm 8.70$ , and during the post-test, it was  $-33.20^{\circ} \pm 11.77$ . The mean difference between the pre-test and post-test was  $1.94^{\circ} \pm 4.46$ , with a p-value of 0.13. The effect size, Cohen's d, was 0.44.

In terms of the time to reach maximal hip belt medial, the mean during the pre-test was  $0.67s \pm 0.09$ , and during the post-test, it was  $0.68s \pm 0.10$ . The mean difference between the pre-test and post-test was  $-0.01s \pm 0.03$ , with a p-value of 0.34. The effect size, Cohen's d, was calculated to be -0.27. The pre-test and post-test values were found to be similar, and no statistically significant differences were observed.

The mean of maximal hip belt lateral (Figure 13) during the pre-test was  $-31.85^{\circ} \pm 5.53$ , and during the post-test, it was  $-33.93^{\circ} \pm 6.56$ . The mean difference between the pre-test and post-test was  $2.08^{\circ} \pm 5.66$ , with a p-value of 0.19. The effect size, Cohen's d, was calculated to be 0.37.

In terms of the time to reach maximal hip belt lateral, the mean during the pre-test was  $0.68s \pm 0.04$ , and during the post-test, it was  $0.68s \pm 0.06$ . The mean difference between the pre-test and post-test was  $0.00s \pm 0.05$ , with a p-value of 0.91. The effect size, Cohen's d, was calculated to be 0.03. The pre-test and post-test values were found to be similar, and no statistically significant differences were observed.

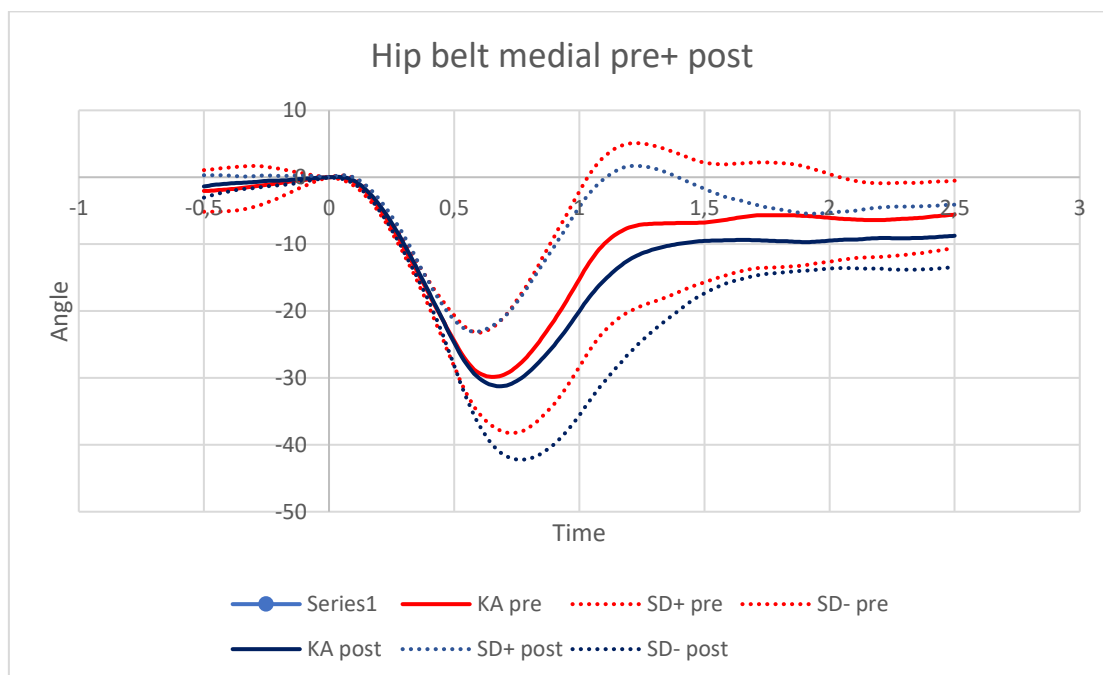


Figure 12. Change in hip belt in medial perturbation condition relative to the instant of perturbation onset.

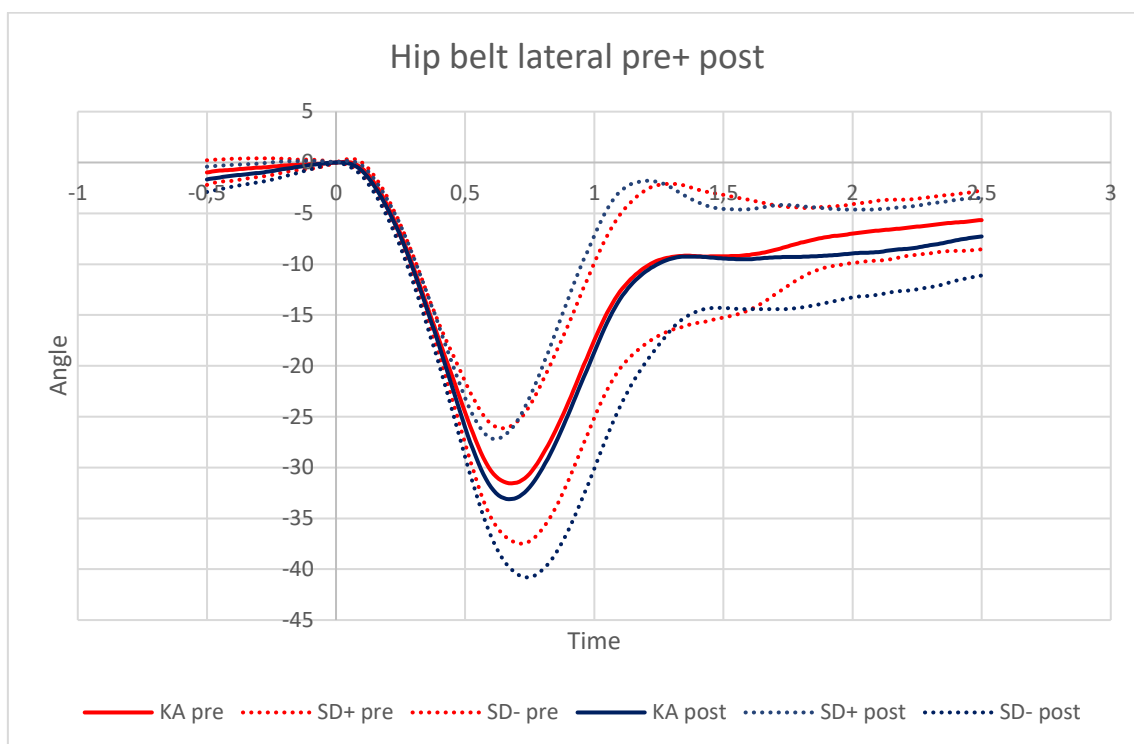


Figure 13. Change in hip belt in lateral perturbation condition relative to the instant of perturbation onset.

#### 11.4 Knee distance

The mean of maximal knee distance medial (Figure 14) during the pre-test was  $-2.30^{\circ} \pm 9.50$ , and during the post-test, it was  $0.78^{\circ} \pm 10.16$ . The mean difference between the pre-test and post-test was  $-3.08^{\circ} \pm 6.76$ , with a p-value of 0.11. The effect size, Cohen's d, was -0.46.

In terms of the time to reach maximal knee distance medial, the mean during the pre-test was  $0.78s \pm 0.32$ , and during the post-test, it was  $0.79s \pm 0.33$ . The mean difference between the pre-test and post-test was  $-0.01s \pm 0.22$ , with a p-value of 0.81. The effect size, Cohen's d, was calculated to be -0.07. The pre-test and post-test values were found to be similar, and no statistically significant differences were observed.

The mean of maximal knee distance lateral (Figure 15) during the pre-test was  $6.43^{\circ} \pm 5.68$ , and during the post-test, it was  $6.23^{\circ} \pm 6.23$ . The mean difference between the pre-test and post-test was  $0.19^{\circ} \pm 6.61$ , with a p-value of 0.91. The effect size, Cohen's d, was calculated to be 0.03.

In terms of the time to reach maximal knee distance lateral, the mean during the pre-test was  $0.65s \pm 0.28$ , and during the post-test, it was  $0.63s \pm 0.19$ . The mean difference between the pre-



test and post-test was  $0.02s \pm 0.32$ , with a p-value of 0.83. The effect size, Cohen's d, was calculated to be 0.06. The pre-test and post-test values were found to be similar, and no statistically significant differences were observed.

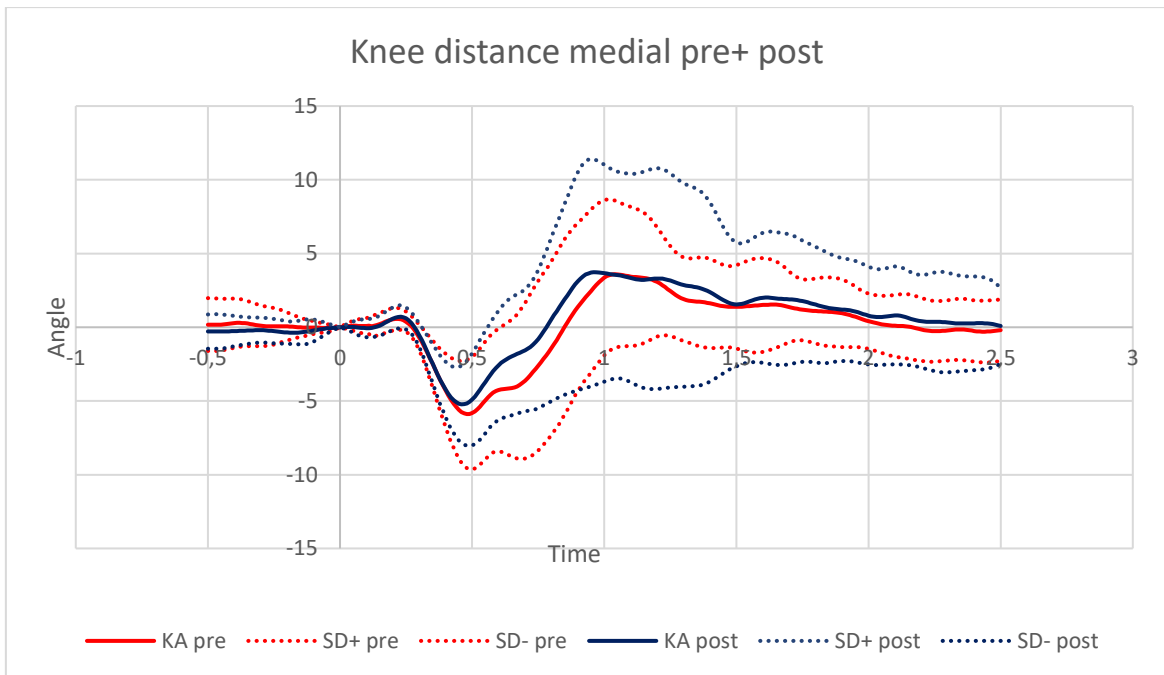


Figure 14. Change in knee distance in medial perturbation condition relative to the instant of perturbation onset.

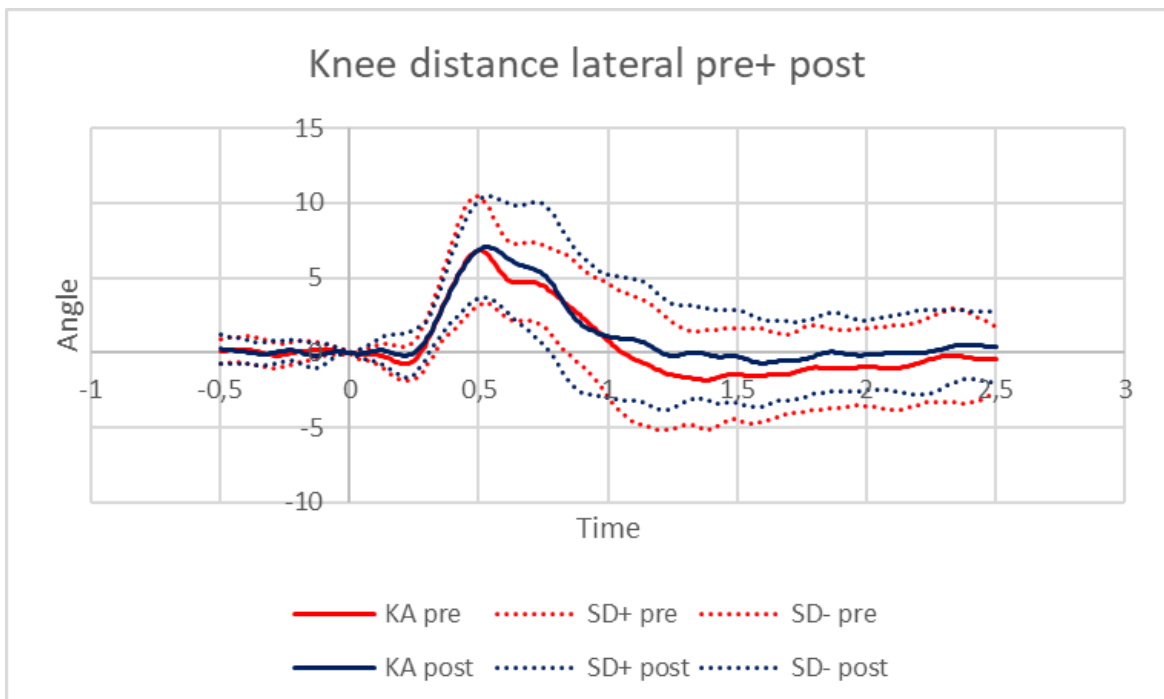


Figure 15. Change in knee distance in lateral perturbation condition relative to the instant of perturbation onset.

When we compared individual participants' maximal pre-test values with their post-test values (Tables 2 & 3) only statistical differences were found in the mean values of time to reach pelvis tilt maximal and change values (p-value 0.02).

Table 2. The mean difference values of maximal values and change values.

	<b>pre</b>	<b>post</b>	<b>dif</b>	<b>cohen</b>	<b>sigf</b>
pelvis tilt	-1.10±5.93	-1.87±6.67	0.77±8.03	0.10	0.70
pelvis drop med	1.03±4.42	0.53±3.63	0.50±5.83	0.09	0.72
pelvis drop lat	0.62±2.24	1.05±2.04	-0.43±2.45	-0.17	0.47
hip belt med	-29.03±12.47	-30.70±15.32	1.66±4.21	0.40	0.11
hip belt lat	-29.77±10.23	-31.68±11.36	1.91±5.01	0.38	0.12
knee dist med	7.40±5.62	7.49±6.13	-0.09±5.49	-0.02	0.95
knee dist lat	7.61±3.17	8.01±2.67	-0.39±2.46	-0.16	0.51

\*pre= before fatigue

\*\*post= after fatigue

\*\*\*dif= differences between pre-test and post-test

\*\*\*\*p-value  $p < 0,05$

Table 3. The mean values of time to reach maximal and change values.

	<b>pre</b>	<b>post</b>	<b>dif</b>	<b>cohen</b>	<b>sigf</b>
pelvis tilt	0.56±0.14	0.57±0.14	-0.01±0.01	-0.61	0.02
pelvis drop med	0.97±0.28	1.10±0.35	-0.13±0.33	-0.39	0.12
pelvis drop lat	0.84±0.32	0.94±0.34	-0.09±0.45	-0.21	0.39
hip belt med	0.64±0.16	0.64±0.17	-0.01±0.03	-0.31	0.21
hip belt lat	0.64±0.16	0.64±0.16	0.00±0.04	0.00	0.97
knee dist med	0.75±0.32	0.77±0.32	-0.01±0.19	-0.07	0.76
knee dist lat	0.63±0.29	0.61±0.21	0.02±0.29	0.08	0.75

\*pre= before fatigue

\*\*post= after fatigue

\*\*\*dif= differences between pre-test and post-test

\*\*\*\*sigf=  $p < 0,05$

### **11.5 Comparison of Pre-test and Post-test Results Within Participants**

Our aim was to visually examine the correlation between pre-test and post-test measurements. Scatter plots offer a comprehensive graphical representation of the distinct datasets, enabling the evaluation of their distribution and potential trends pertaining to the variables under investigation. Although only statistical differences were found in pelvis tilt time to reach maximal value, and otherwise no statistical differences in our study were observed, the usability of the measurement protocol could still be applicable. Generally, differences between the pre-test and post-test with-in participant were observed mostly in lateral perturbations, while medial trials were closely aligned to each other's as are seen as an example in figure 16.

Moreover, an examination of the data point distribution allows for the identification of any potential trends. The proximity of the data points to the diagonal serves as an indicator of the level of similarity or change between the pre-test and post-test measurements. Notably, if the data points closely align along the diagonal line, it suggests consistent effect between participants and minimal alterations between the two measurements.

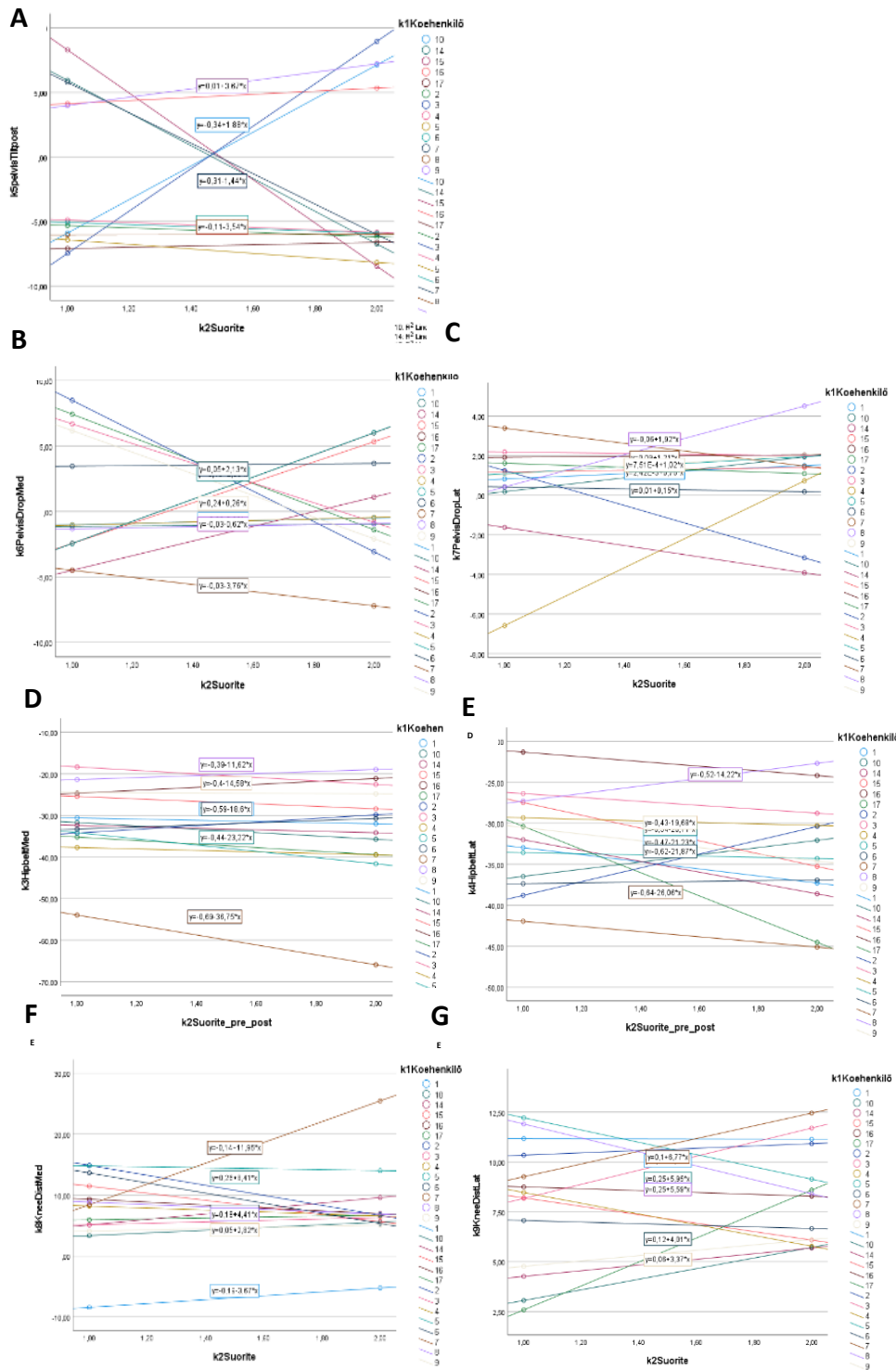


Figure 16. Scatter plot analysis was employed to provide a visual representation of the data obtained from the pre-test (1.00) and post-test (2.00) measurements (denoted as k2Suorite\_pre\_post). Each participant (1-17, denoted as k1Koehenkilö) was represented by colorful circles on the plot. The interconnecting lines between the circles depicted the relationship between the pre-test and post-test measurements for each participant.

## 12 DISCUSSION

With this study the purpose was to evaluate how one of the main restrictive components of the performance/sport, the fatigue, influence on the lower limbs motor control. Notably, to best of our knowledge this was the first study to investigate this phenomenon by using perturbed postural balance method on youth alpine skiers. The hypothesis, **Fatigue impairs movement control resulting more knee medialization, pelvis lateral movement and anterior pelvis tilt in response to the perturbation was rejected.**

Only statistical differences were found between the pre-test and post-test in Pelvis tilt time to reach maximal values. Our results are consistent with the study conducted by Benjaminse et al., (2008), as no significant differences were observed in maximal knee valgus angle and knee flexion angle between the pre-fatigue and post-fatigue postural balance conditions. However, because of the feasibility of the results it may be assumed that usability of perturbed balance test for the pre-test and post-test was quite good in all direction (anterior-posterior, medial-lateral), and this follows to study Lesch et al., (2021).

The ability to maintain postural balance is negatively affected when individuals are unexpectedly perturbed (Steinberg et al., 2022). The process of postural adjustment following perturbation involves the recognition of body segment movements through visual, vestibular, and proprioceptive sensory inputs, the integration of this information within the central nervous system (CNS), and the execution of an appropriate motor response (Ritzmann et al., 2016). Further, the unexpected external perturbation makes individuals to count predominantly on reactive balance control (Gerards et al., 2021). Reactive postural responses are elicited in response to abrupt alterations in posture or changes in the support surface. Upon encountering a perturbation, the initial response mediated by the spinal cord is typically insufficient to restore balance and stability. The neuromuscular system's inability to respond promptly and effectively can lead to abnormal joint biomechanics and an inability to maintain stability. This can initiate a chain reaction of prolonged responses and potentially result in injury (Morris Amanda et al., 2023). The aim of our study was to use instrumented treadmill on investigating perturbed balance control, more closely the lower limb alignment to response to external perturbation. We assumed that this measurement protocol could simulate the demands of a race run alpine skiing, thus the investigation of neuromechanical responses can offer valuable insights in identifying athletes who may be at a higher risk of injury. Further, the measurement tasks and protocol were chosen to be suitable for young athlete. Single-leg tasks

impose greater functional demands compared to tasks involving both legs, as they require the loaded leg to support the body while the center of mass decelerates in both vertical and horizontal directions. This challenging nature of single-leg tasks places a greater emphasis on neuromuscular control, stability, and coordination to maintain balance and control during the deceleration phase. The need to stabilize and control the body's movement in multiple planes of motion adds complexity to the task and highlights the importance of efficient motor control strategies in single-leg activities (Bedo et al., 2022). Given the extensive body of literature examining the impact of fatigue on postural sway, our consideration led us to identify the single-leg stance as the optimal task for our study. This task is believed to be more suitable due to its increased level of difficulty compared to bipedal tasks, making it more likely to exhibit greater sensitivity to fatigue (Kozinc et al., 2021). Furthermore, unexpected perturbations challenge the reactive postural control mechanisms, which are responsible for rapidly adjusting the body's posture and muscle activation patterns. These mechanisms involve complex interactions between sensory feedback, neural processing, and muscular coordination. When faced with unexpected perturbations, the reactive responses may be insufficient or delayed, further contributing to postural instability.

The fatigue is known to be factor affecting negatively to neuromuscular and musculoskeletal systems (Benjaminse et al., 2008; Koller et al., 2015). The apparent influence from fatigue is the decreased motor control function, altered joint stability, decreased postural balance control and insufficient proprioception (Benjaminse et al., 2008). Gribble, (2004) highlighted that the presence of fatigue can lead to modifications in somatosensory input, potentially causing impairments in neuromuscular control. These impairments can manifest as deficits in postural control, indicating a compromised ability to maintain stable balance. Furthermore, it has been observed that fatigue may exert an influence on the muscles surrounding the knee and hip joints, potentially leading to postural control impairments in both the frontal and sagittal planes. These impairments can express as deficits in postural control, indicating a compromised ability to maintain stable balance. Gribble et al. (2004) also manifested that fatigue may have influence on knee and hip muscles which can cause postural control impairments in both frontal and sagittal planes. In their study, Bedo et al. (2022) determined that the state of fatigue had a significant impact on the kinematics of the lower limbs. Specifically, they observed an increase in knee valgus angle during the performance of single-leg tasks. Additionally, they noted a decrease in both knee and hip flexion during the execution of sidestep cutting maneuver and drop vertical jump tasks following the fatigue

protocol. Furthermore, in the presence of fatigue, there was an increase in hip adduction during the SCM task and an increase in hip adduction during the single- leg landing task. Cortes et al., (2014) investigated the effects of fatigue accumulation on knee and hip kinematics during a crossover single leg hop task, revealing a progressive decrease in knee flexion and an increase in knee adduction as fatigue levels increased due to multiple rounds of a fatigue protocol. In another study by Lucci et al., (2011), fatigue was found to result in significantly increased knee internal rotation and decreased hip flexion, knee flexion, and hip internal rotation during unanticipated side-stepping tasks. These findings highlight the influence of fatigue on kinematic parameters and provide valuable insights into the alterations in joint movement patterns associated with fatigue-induced changes in neuromuscular control. It is important to note that most lower limb kinematic studies have utilized various jump, sidestep, or running tests. As a result, direct comparisons between our study and these previous investigations may be challenging due to differences in test protocols and methodologies. Although our study revealed statistical differences in maximal posterior tilt between the pre-test and post-test, it can be attributed to the constraints imposed by the ski boot on posture. Otherwise, our study did not reveal any statistically significant differences in the lower limb kinematic variables between the pre-test and post-test conditions by using perturbed postural balance test. However, it is worth noting that certain changes could have been observed at the individual level. The wide range of individual performance changes and the deviation among participants suggest considerable variability in responses to the intervention. The participants' RPE ranged from 14 to 17, and the time they took to return to the treadmill after the fatiguing box jump test varied from 2.10 minutes to 7.15 minutes. Considering these factors, it is reasonable to assume that the fatigue level had reduced to a minimum. The specific tasks and conditions employed in each study can significantly influence the observed lower limb kinematic patterns. Additionally, the ski boot may have influence on the results by providing an increased support base, which can potentially facilitate easier balance control. Hence, caution should be considered when drawing direct comparisons between our results and those reported in the existing literature.

Numerous studies have documented weaknesses in hip extension, external rotation, and abduction among individuals who exhibit valgus during dynamic tasks, or even had experienced the knee injuries. These findings highlight the potential association between hip muscle deficiencies and the development of faulty movement patterns and subsequent knee injury susceptibility (Ellenberger et al., 2021; Rinaldi et al., 2022). Both hip abduction and

external rotation are primarily influenced by the activation of the gluteus medius and gluteus maximus muscles. These muscles play a crucial role in providing stability to the pelvis and functioning of the lower extremities. Dysfunction or weaknesses in the gluteus medius and gluteus maximus muscles have been frequently associated with various knee, pelvis, and hip disorders. Understanding the importance of these muscles is crucial in addressing and managing conditions affecting the knee, pelvis, and hip (Rinaldi et al., 2022). Furthermore, a multitude of studies have provided evidence indicating that increased strength in the gluteus medius and gluteus maximus muscles can serve as a protective factor against dynamic knee valgus (DKV) and non-contact anterior cruciate ligament (ACL) injuries. Additionally, several authors have demonstrated the impact of hip abduction moments on DKV during jump landing tasks (Lessi et al., 2017; L.-I. Wang, 2011). Despite the absence of statistical differences between the pre-test and post-test measurements in our study, it would be premature to conclude that fatigue had no influence. The mean value of the RPE was  $15.64 \pm 0.93$ , indicating that the fatigue protocol applied was sufficiently strenuous to induce exhaustion but not muscle fatigue. However, the mean recovery time for the fatigue to perturbation task was  $4.01 \pm 1.20$  minutes, which is considered a relatively long duration for recovery. This extended recovery period may have contributed to the lack of significant differences observed. A recent study conducted by Bedo et al. (2020) employed a comprehensive fatigue protocol that included tasks such as jumping, sidestep cutting, sprinting, and landing. The findings of the study demonstrated a significant increase in single-leg postural sway and a decrease in maximal strength as a result of the fatigue protocol. However, it is important to note that both the postural sway and maximal strength levels returned to their baseline values within a 5-minute recovery period. Our results are consistent with the findings of Bedo et al. (2020) and highlight the transient nature of the effects of fatigue on postural sway and motor control.

It is important to note that recent systematic reviews have also indicated that fatigue does not significantly affect most knee kinetic and kinematic variables (Benjaminse et al., 2019). Further, it should be acknowledged that balance control in perturbed balance tasks requires effective muscle activation in both the anterior-posterior and medial-lateral directions. Our study involved a group of highly skilled youth alpine skiers, who exhibited a significant level of training and proficiency in adopting the specific knee and hip positions necessary for the balance task. The participants' familiarity with these positions played a vital role in their ability to effectively perform the task. It is important to highlight that alpine ski racing



necessitates similar muscle activation patterns as those observed in our balance task. The expertise and extensive training of our participants in alpine skiing likely contributed to their competence in maintaining balance and executing the required movements. Further research is warranted to explore the complex interplay between fatigue, balance control, and muscle activity in these specific tasks.

Postural balance and motor control are fundamental aspects in most sports (Sarabon & Hirsch, 2016). These abilities play a crucial role in maintaining stability and executing precise movements, contributing to overall athletic performance and injury prevention. Competitive alpine skiing is characterized as a physically demanding sport that imposes substantial physiological stresses on the bodies of skiers. Ellenberger et al. (2021) quantified that the knee joint experiences significant joint moment stress, up to 1.75 times the body weight, may causing high degrees of flexion and valgus alignment. Numerous studies have documented muscular weakness in hip extension, external rotation, and abduction among individuals who exhibit valgus alignment during dynamic activities or are prone to knee injuries (Cibulka & Bennett, 2020; Rinaldi et al., 2022; L.-I. Wang, 2011). Several studies have consistently indicated that improved strength in the gluteus medius and gluteus maximus muscles can play a protective role in reducing dynamic knee valgus and thereby lowering the risk of non-contact anterior cruciate ligament injuries. Additionally, several authors have provided evidence demonstrating the influence of hip abduction moments on dynamic knee valgus (DKV) during jump landing (Lessi et al., 2017; Rostami et al., 2019; L.-I. Wang, 2011). Based on those, postural balance and motor control are fundamental in preventing sport injuries in alpine skiing due to the demanding nature of the sport and the unique challenges it presents. Alpine skiing involves high speeds, varied terrain, and abrupt changes in direction. Maintaining postural balance and having precise motor control are crucial for skiers to stay stable and in control of their movements. This helps them adapt to uneven surfaces, maintain proper body alignment, and minimize the risk of falls or collisions. Secondly, effective postural balance and motor control help reduce the risk of injury by allowing skiers to maintain optimal joint alignment and distribute forces appropriately. By staying balanced and in control, skiers can better absorb impact and stress, reducing the strain on their muscles, ligaments, and joints. This type of perturbed balance test can serve as an indicator of lower limb control deficiencies. Additionally, this can help prevent common skiing injuries such as knee ligament tears, ankle sprains, and fractures. As we know, ACL tears are the predominant type of injury observed in alpine ski racing, leading to substantial time loss from the sport.

The etiology of ACL injuries has been extensively studied. However, there is a scarcity of scientific data regarding the internal neuromuscular factors involved in the injury process (Jordan et al., 2017). Remarkably, our study successfully demonstrated the ability to distinguish between individuals, and our future goal is to extend this capability to predict the risk of injury. Thirdly, alpine skiing often involves unexpected changes in the skiing environment, such as uneven terrain, or sudden obstacles. Good postural balance and motor control enable skiers to quickly adapt and respond to these perturbations. They can make rapid adjustments in their body position, weight distribution, and muscle activation to regain stability and avoid injury. Proper postural balance and motor control contribute to efficient skiing technique. Skiers who have a solid foundation of balance and control can execute movements more smoothly and efficiently, conserving energy and reducing the risk of fatigue-related errors. This helps to maintain consistent performance throughout a skiing session and decreases the likelihood of making mistakes that could lead to injuries. On the other hand, developing postural balance and motor control skills in alpine skiing enhances skiers' confidence and focus. When skiers feel confident in their ability to maintain balance and control their movements, they can concentrate more on their technique, strategy, and overall safety. This mental aspect plays a vital role in preventing injuries by reducing anxiety and promoting better decision-making on the slopes.

In summary, this study aimed to assess the impact of fatigue on lower limb motor control among youth alpine skiers using a perturbed postural balance method. The perturbed balance test demonstrated good usability for assessing postural control in multiple directions, consistent with previous research. However, this study did not reveal significant differences in lower limb kinematics following fatigue, likely due to the relatively long recovery period. Overall, this study contributes valuable insights into the complex relationship between fatigue, postural balance, and motor control in alpine skiing, emphasizing the importance of individualized assessments and the potential for injury prevention through improved balance and control.

One of the limitations commonly encountered in research studies is a small sample size. Limited sample sizes can restrict the generalizability of the findings and reduce the statistical power to detect significant effects. It is important to acknowledge that the results obtained from a small sample may not be representative of the broader population, leading to potential biases and limited external validity. However, it should be noted that conducting biomechanical research of this nature, which involves a 3D motion capture system consisting

of 10 reflective-marker-based cameras and an instrumented treadmill, is a time-consuming process. Due to the complexity and technical requirements of the equipment, investigating a large sample size becomes challenging. In addition, the potential local participant population size is limited preventing us recruiting more participants. Further, a control group would have allowed for comparison against a non-athlete, providing a baseline for assessing the effects of fatigue or perturbation. Without a control group, it becomes challenging to attribute the observed changes solely to the experimental factors under investigation. The design of the fatigue protocol is a crucial factor to consider. Although the 90-second box-jump test, which is part of the Alpine Canada Physical Fitness testing, serves as a sport-specific fatigue test for alpine skiers, the time interval between fatigue and the perturbation measurement was found to be too long, resulting in a substantial recovery period (Bedo et al., 2022). These variations in the protocol may introduce differences in the level of fatigue induced, potentially impacting the outcomes related to postural control. The design of the fatigue protocol is a critical consideration. These variations may lead to differences in the level of fatigue induced, potentially influencing the postural control outcomes. The presence of a learning effect can introduce bias and influence the results of postural control studies. Participants may become more proficient in performing the task over time, leading to improved postural control regardless of the fatigue or perturbation effects. It should be noted that during the ski boot measurement trials, the subjects had already completed a minimum of six perturbation trials. This sequence of perturbation trials could potentially introduce a short-term learning effect on the subjects' performance and the improvement in balance performance might have been partially learned after the initial testing session of a single perturbation session (Hu et al., 2023). The treadmill used in our study had a uni-directional belt movement, which enabled the participants to anticipate the perturbations, even when the timing between perturbations was randomized. It is worth noting that in our previous study conducted by Lesch et al. in (2021), we have already conducted reliability and accuracy measurements. The results of that study were consistent with previous research that utilized a multi-directional movable force plate, as demonstrated in the study by Piirainen et al., (2013). Using RPE as a fatigue monitor might not be the most optimal metric for measuring fatigue levels in this type of study. However, we adopted for RPE due to its ease of use and practicality. Lastly, it is important to acknowledge that our study was conducted solely in a laboratory setting, which may not fully replicate the conditions of a real alpine ski run. In the laboratory, the only controlled variable was the perturbation of the instrumented treadmill. However, in a real alpine ski run, various

environmental and psychological factors can come into play and potentially impact performance.

In the future, incorporating electromyography (EMG) measurements alongside joint kinematics and kinetics would enable a comprehensive assessment of the mechanisms involved in maintaining balance. EMG data can provide information about various factors such as anticipatory muscle activity, latency or reaction time, muscle fatigue detection, reflexive activity, and muscle co-activation, which are all relevant to motor control of postural balance.

Moreover, previous studies have employed percutaneous electrical stimulation of peripheral nerves to assess H-reflexes during perturbations, as demonstrated by Piirainen et al. (2013), and transcranial magnetic stimulation (TMS) to assess corticospinal responses, as demonstrated by Hu et al., (2022). This additional measurement technique can be used to evaluate spinal and corticospinal sensitivity during postural balance maintenance and motor control. By integrating these methods, it would be possible to gain a more comprehensive understanding of the neuromuscular mechanisms underlying balance control. Furthermore, exploring the possibility of incorporating mixed directions and speeds of perturbations within a single trial can further enhance our understanding of the neuromuscular function of motor control. By introducing variability in the perturbation stimuli, we can examine how the neuromuscular system adapts to different challenges and assess the robustness of balance control mechanisms. This approach would provide valuable insights into the versatility and adaptability of the human motor control system in maintaining postural stability under diverse conditions.

## **13 CONCLUSIONS**

In conclusion, this study aimed to examine the influence of fatigue on lower limb motor control, specifically in the context of perturbed postural balance, among youth alpine skiers. The study findings led to the rejection of the hypothesis. Despite of the statistical difference in pelvis tilt time to reach maximal, it is reasonable to conclude that no significant differences were observed between the pre-test and post-test measurements, indicating that fatigue did not have a significant effect on postural balance control, including knee alignment (knee valgus) and hip kinematics (hip flexion and hip abduction). However, it is worth noting that the perturbed balance test used in the study demonstrated consistency in assessing postural control in multiple directions, even though the repeatability was not actually measured. Further, our findings are consistent with the previous study by Lesch et al. (2021). Further research is warranted to explore additional factors that may influence lower limb motor control and to enhance our understanding of the complex interactions between fatigue, postural balance, and athletic performance in alpine skiing and other sports.

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