PERIODIZING SKILL-TRAINING - THE EFFECT OF A PLANNED SKILL-TRAINING BREAK ON HANDSTAND SKILL ACQUISITION

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Biology of Physical Activity Master`s Thesis
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Spring 2022

TIIVISTELMÄ

Hänninen, H. 2022. Taitoharjoittelun periodisointi – Taitoharjoitustauon vaikutus käsinseisonnan kehittymiseen. Liikuntatieteellinen tiedekunta, Jyväskylän yliopisto, valmennus- ja testausopin pro gradu -tutkielma, 56 s.

Tutkimuksen tarkoituksena oli selvittää kahden viikon taitoharjoittelutauon vaikutus käsinseisontataidon kehittymiseen 13 viikon harjoitteluintervention aikana asetelmassa, missä käsinseisonnan fyysisiä pohjaominaisuuksia ylläpidetään 2 viikon mittaisen taitoharjoittelutauon aikana. Vaikka sekä taitoharjoittelua että fyysisen harjoittelun periodisointia on tutkittu, juuri fyysisesti vaativan taitoharjoittelun periodisoinnista ei vaikuta olevan aiempaa tutkimusta. Pyrkimyksenä oli selvittää, kantaako loogisesti suunnitellun taitoharjoittelujakson vaikutus tauon yli, jos voimatasojen ei anneta pudota sen aikana.

Fyysisen harjoittelun periodisointiin liittyvä tutkimusnäyttö on osoittanut periodisoidun harjoittelun olevan urheilusuorituskyvyn kannalta periodisoimatonta harjoittelua tuloksekkaampaa, ja juuri blokkiperiodisoinnin on osoitettu olevan yksi toimivimmista periodisointimalleista – ellei jopa toimivin. Taitoharjoittelun adaptaatioihin liittyvän kirjallisuuden perusteella vaikuttaa todennäköiseltä, että osa taitoharjoittelun hermostollisista adaptaatioista voi toimia blokkiperiodisoinnissa hyödynnettävien residuaalivaikutusten tavoin. Voiman tiedetään heikkenevän nopeammin, joten taitoharjoitustauon aikana täytyy tehdä ylläpitävää voimaharjoittelua käsinseisontaan liittyvien lihasryhmien osalta.

Keskimääräinen käsinseisonnan tasapainoiluaika ($n = 41$) kehittyi 1,94 ± 4,40 sekunnista 6,46 ± 7,88 sekuntiin ($p < 0,001$), ja laadullinen käsinseisonta-asento (asteikolla 1–3) kehittyi 0,80 ± 0,95 arvosta lukemiin 1,56 ± 0,59 ($p < 0,001$). Ryhmien välillä ei ollut tilastollisesti merkittävää eroa tasapainoiluajan ($p = 0,609$) eikä laadullisen kehityksen ($p = 0,589$) välillä. Käsinseisonnan tasapainoiluajan kehitys oli tilastollisesti merkitsevää ($p < 0,001$) jokaisella ryhmällä, ja käsinseisonta-asennon laadun kehitys oli tilastollisesti merkitsevää harjoitustauon pitäneillä ryhmillä B ja C ($p = 0,011$ ja $0,001$), mutta ei vain käsinseisontaa harjoitelleella ryhmällä A ($p = 0,059$). Harjoitustauolla ei ollut vaikutusta taitojen kehittymiseen missään tutkimuksen vaiheessa, ja tauon ajoituksella oli merkitystä vain keskimmäisen välitestin kohdalla. Ylävartalon punnerrusvoiman lähtötaso korreloi tasapainoiluajan kehittymisen kanssa ($r = 0,537$, $p = 0,021$), mutta ei käsinseisonta-asennon kehittymisen kanssa ($r = -0,002$, $p = 0,503$).

Tutkimuksen löydökset vahvistivat hypoteesin, että loogisesti periodisoitu taitoharjoittelujakso voi sisältää täysiä taukoja spesifistä taitoharjoittelusta, jos taitoon liittyvien fyysisten pohjaominaisuuksien ei anneta heikentyä tauon aikana. Taitojen oppimiseen ja muistiin liittyvän kirjallisuuden perusteella vaikuttaa siltä, että oppimiseen liittyvät hermostolliset muutokset ovat verrattain pysyviä, mikä selittäisi tämän tutkimuksen tulokset. Vuoden 2021 covid-rajoitusten vuoksi tässä tutkimuksessa ei kuitenkaan tehty laboratoriomittauksia, joten havaittujen suorituskyvyllisten tekijöiden taustamekanismeista ei tämän perusteella voida sanoa paljoa. Tulokset ovat kuitenkin lupaavia, ja tarkempaa mekanismeihin syventyvää tutkimusta tarvitaan.

Asiasanat: käsinseisonta, taitoharjoittelu, blokkiperiodisaatio

ABSTRACT

Hänninen, H. 2022. Periodizing skill-training – The effect of a planned skill-training break on handstand skill acquisition, University of Jyväskylä, Science of sports coaching and fitness testing Master's thesis, 56 pp.

The purpose of the present study is to examine the effects of a planned 2-week skill training break on skill acquisition during a 13-week intervention study on periodized handstand skill training in a setting, where the key prerequisite physical attributes are maintained during the skill-training break. The study set out to test whether a properly executed accumulation phase carries residual effects spanning over a 2-week period of zero handstand skill training, provided that the prerequisite strength is maintained during the break. Periodization of physically demanding motor skills has not been studied.

Evidence on periodization for sports performance has shown periodized training to be superior to non-periodized training, and block periodization has been demonstrated to be among the best periodization models. Literature on neural adaptations behind motor skill learning suggests that provided the skill is acquired to a high-enough level utilizing effective methodologies, the time-course of skill-training adaptations allows for periods of non-use without detrimental effects on performance. While skills have been shown to be relatively permanent under some circumstances, strength has been shown to decay with time. Therefore, successful periodization of physically demanding motor skill training requires maintenance of those physical prerequisites that have been shown to decay faster.

The average handstand balancing time across all groups ($n = 41$) went from 1.94 ± 4.40 seconds to 6.46 ± 7.88 seconds ($p < 0.001$) and the qualitative handstand form (on a scale of 1–3) went from 0.80 ± 0.95 to 1.56 ± 0.59 ($p < 0.001$), with no statistically significant between-group differences in balancing time ($p = 0.609$) or handstand form ($p = 0.589$). Progress in handstand balancing time between pre- and post-measurements was statistically significant for all groups, and qualitative progress in handstand form across the intervention was statistically significant for groups B ($p = 0.011$) and C ($p = 0.001$), but not for group A ($p = 0.059$). Comparison between handstand-only group (A) and skill-training break groups (B+C) showed no statistically significant differences associated with the presence of the skill-training break, and comparison between groups B and C showed a statistically significant difference at the 2nd mid-measurement, but not in any other point of the intervention. Initial upper body pushing strength correlated with progress in handstand balancing time ($r = 0.537$, $p = 0.021$), but not in handstand form ($r = -0.002$, $p = 0.503$).

Main findings of the present study confirmed all hypotheses without surprises, suggesting that a logically designed periodization plan for skill acquisition can include total breaks from specific skill-training, provided that the physical prerequisites with higher decay rate are maintained or trained during the skill-training break. Literature on skill acquisition and retention suggests that certain neural adaptations are more resilient to decay over time, and the findings of the present study line up with this notion. However, due to covid-related restrictions no laboratory measurements were performed, thus limiting the ability to speculate on the underlying neural mechanisms. The results are promising, and further study on the subject is both warranted and needed.

Key words: hand-balancing, block periodization, skill acquisition

CONTENTS

1 INTRODUCTION

At its’ core, periodization is about designing a macro-level blueprint and logical framework of training based on what is known about adaptations to different types of training stimuli (Stone et al. 2021). As far as strength, power or endurance goes, periodization for sports performance has been studied extensively (Plisk & Stone 2003; Lyakh et al. 2016; Stone et al. 2021). Data on training volumes and intensities needed for improvement versus maintenance exists (Bickel et al. 2011; Macpherson & Weston 2015; Iversen et al. 2021), and the effect of detraining has been studied as well (Bosquet et al. 2013; Sousa et al. 2019). In several studies block periodization has been documented as superior to other periodization models (Painter et al. 2012; Rønnestad et al. 2019; Stone et al. 2021). Extensive body of literature on behavioural and neurophysiological adaptations to motor skill training exists (Spampinato & Celnik 2021) and some evidence on skill permanence suggests that provided an effectively executed skill acquisition phase, a following nonpractice period has no negative effect on performance of the acquired skills (Arthur et al. 1998; Ward et al. 2012; Spampinato & Celnik 2021). Despite the body of literature around both skill training adaptations and periodization for sports performance, periodization of physically demanding motor skills has yet to be studied (Farrow & Robertson 2017).

Learning and motor skill acquisition is a set of internal physiological processes leading to relatively permanent change in the ability to produce skilled movements (Kantak & Winstein 2012). The formation of new synapses is a crucial part of this set of processes (Wymbs et al. 2016). The stages and mechanisms of synaptogenesis are somewhat known (Bramham & Wells 2007; Rudy 2014; Shors 2016), and the last stage of synaptogenesis seems to make the connection relatively permanent (Kwapis & Helmsletter 2014; Hsieh et al. 2017). Studies on skill retention and skill decay suggest that the time from learning isn’t as important factor of skill retention or decay, as the methodology of learning or testing, or the nature of the skill (Arthur et al. 1998; Ward et al. 2012). The same Arthur et al. (1998) review showed that cognitive skill decay faster than motor skills. It seems plausible that some neural adaptations of motor learning might be practically permanent.

Physical prerequisites of motor skills are an important factor. The time course of atrophy and strength loss following detraining depends on the age and level of the practitioners, yet even the fastest decay rate doesn’t show meaningful decay in under four weeks (Bosquet et al. 2013;

Sousa et al. 2019). One short and focused strength training session a week has been shown to prevent strength loss across several age groups (Iversen et al. 2021). The skill of hand-balancing requires skill, strength, and certain amount of flexibility, and so the study of permanence requires a setting where the physical prerequisites are maintained during the skill training break. The most important prerequisites include namely the controlled flexibility of shoulder flexion and wrist extension, as well as strength of wrists, elbows, and shoulders (Hedbávný et al. 2013b; Kochanowicz et al. 2018). The purpose of the present study was to examine whether a 2-week break in skill training affects motor learning if the prerequisites are trained during said break.

2 SKILL ACQUISITION AND RETENTION

The adaptability arising from the capacity to acquire and retain novel motor skills is essential for everyday life (Kantak & Winstein 2012; Hermsdorf et al. 2020). Motor skill itself can be defined as an ability to achieve a movement-related goal with great consistency under a wide variety of conditions, i.e., control over a goal-directed movement (Higgins 1991), while motor learning can be defined as the set of processes leading to improved capability for motor skill performance (Kantak & Winstein 2012). Recent studies have provided insights into the distinct neurophysiological processes that underlie the complex phenomenon of motor learning (Spampinato & Celnik 2021), each of which is thought to involve different brain areas and neuronal computations (Haith & Krakauer 2013; Taylor et al. 2014). Learning new skills or calibrating known ones require the engagement of several plastic adaptation mechanisms in the cerebral cortex, cerebellum, and striatum (Dayan & Cohen 2011; Penhune & Steele 2012; Caligiore et al 2017). It is important to note that motor skill learning – the set of internal processes leading to improved performance – is distinct from performance itself, and some training procedures that lead to better skill acquisition performance within the session lead to worse outcomes in retention (Kantak & Winstein 2012).

The two major forms of synaptic plasticity observed in mammalian central nervous system are long-term potentiation (LTP), a long-lasting activity-dependent increase in excitatory synaptic strength, and long-term depression (LTD), a long-lasting decrease in synaptic efficacy (Kumar 2011). The majority of excitatory neurotransmission is mediated by the amino acid glutamate, acting on ionotropic and metabotropic receptors throughout the central nervous system (Gladding et al. 2009). LTP is generally considered the closest neural model for the cellular mechanism involved in learning and memory storage - along with other forms of synaptic plasticity (Baudry et al. 2011; Kumar 2011; Shors & Matzel 1997).

The well-observed phenomenon of notable increases in an individual's maximal strength especially within the first four weeks of starting strength training is generally explained by the neural adaptation paradigm (Kidgell & Pearce 2011; Škarabot et al. 2021), since the time course of morphological adaptations unrelated to hypertrophy appear to be slower (Folland & Williams 2007). The training-related improvements in muscle strength occurring even with a notable absence of muscular hypertrophy are thought to arise as a consequence of improved neural drive to the trained musculature. Neural adaptations to strength training are thought to occur at two levels: a supraspinal and spinal level, involving changes in corticospinal excitation and inhibition, and in spinal motoneurons and inhibitory and excitatory interneurons, respectfully. (Kidgell & Pearce 2011; Škarabot et al. 2021) While neural adaptations to strength training include a component of skill acquisition, strength training elicits neural adaptations distinct from those of skill acquisition (Gabriel et al. 2006; Folland & Williams 2007). In contrast to reorganization of sensorimotor maps of primary motor cortex due to skill training (Spampinato & Celnik 2021), strength training is thought to increase neural drive via alterations in the cortical and/or subcortical structures, such as alterations in inhibitory cortical interneurons and reticular formation of the brainstem (Škarabot et al. 2021).

2.1 Motor skill learning

In their review article, Spampinato & Celnik (2021) described four distinct processes thought to underlie motor learning: error-based learning, reinforcement learning, use-dependent learning, and the use of cognitive strategies. A mismatch between what you think or expect you are doing and what you perceive you are doing drives error-based learning – a process based on continuous calibration around sensory prediction errors. In contrast, reward-prediction errors drive reinforcement learning – a process in which actions leading to perceivably successful outcomes are reinforced and those leading to undesired outcomes are avoided. Use-dependent learning is driven by repetition itself – It is a process where repetition of movements induces learning-related structural and functional changes regardless of the presence of errors. Strategy-based learning refers to meta-cognitive processes and the utilization of explicit knowledge or cognition to complete the motor task or solve to motor problem. (Spampinato & Celnik 2021)

Error-based learning is a short-term process that modifies behaviour based on a comparison of sensory outcomes of expected and realized movements. Several experimental studies and theoretical models have highlighted the role of cerebellum the some of the key processes underlying error-based learning, including the formation of predictions, and encoding sensory prediction errors for calibrating and updating sensory-motor maps. Sensory prediction errors indicate how subsequent movements should be modified to reach a more desirable outcome, thus being vectorial in nature. Due to their vectorial nature, they can be used in developing and calibrating sensory-motor maps to reduce sensory prediction errors. The cerebellar-dependent error-based process is thought to be weighted strongly in early stages of learning, before the task dynamics are learnt and the weight shifts to primary motor cortex, incorporating other forms of learning. (Spampinato & Celnik 2021).

Reinforcement learning relies on exploration around different actions, which are then reinforced based on the outcome – perceived success or failure. The feedback of reinforcement learning is not vectorial, as it doesn't provide information about how a behaviour should be adjusted. Basal ganglia play a key role in reinforcement learning, as both action selection itself and the subsequent feedback of reinforcement are facilitated by dopaminergic neuron activity, which uses reward prediction errors to inhibit unwanted movements while encouraging the selection of desired ones. (Spampinato & Celnik 2021). Reinforcement learning is initially slower than error-based learning but has been shown to lead to longer retention (Therrien et al. 2016). The dopaminergic activity and the action of basal ganglia-thalamo-cortical circuits play a role in eliciting LTP-like changes in M1 (Spampinato & Celnik 2021), thus proposing a mechanism by which motivation can directly affect learning outcomes. Recent studies also show that providing additional positive feedback – regardless of its' honesty – during learning trials enhances motor skill retention (Galea et al 2015; Shmuelof et al 2012; Spampinato et al. 2019), hinting at the subjectivity of "success" and further highlighting the importance of motivation.

Motor actions are also shaped by the history of previous motor actions, even in the absence of information about the movement, the task, or the outcome. Use-dependent learning describes this goal-independent process where motor memories are formed and modified by changing movements to become more like previous movements. Repetition in and of itself reduces undesired movement variability and produces faster movements by facilitation of movement planning. Moreover, mere action observation has been shown to facilitate motor learning via the engagement of mirror neuron system activity. Interestingly, some existing evidence attributes the mechanisms underlying skill acquisition by action observation to the same processes underlying use-dependent learning. The improved motor performance related to the formation, modification, and retention of motor memories via repetitive training has been associated with LTP-like changes in the primary motor cortex. (Spampinato & Celnik 2021)

Neurobiological organisms are complex dynamic systems, making it likely that different forms of learning overlap and interact with each other when acquiring new skills: performance repetition facilitated by use-dependent learning mechanisms results in less unwanted variability, making sensory prediction errors smaller, thus increasing the engaging reinforcement learning mechanisms with greater likelihood (Spampinato & Celnik 2021). Certain training procedures that improve within-session acquisition performance have been shown to be worse for retention than certain training procedures that intentionally introduce certain types of difficulties for the learner within the training session (Kantak & Winstein 2012). Training procedures that improve within-session performance while hindering retention include blocked-order training (Kantak & Winstein 2012), which seems to prioritize elements from use-dependent training over error-based or reinforcement learning as described in the Spampinato et al. review (2021). The procedures that introduce difficulties within the training session but lead to better retention include contextual interference and random-order training (Kantak & Winstein 2012), which prioritize elements of error-based learning as described by Spampinato et al. (2021). Some previously established models propose that the nature of the skill determines the primary brain areas involved – cortico-cerebellar structures in sensorimotor tasks and cortico-striatal system in sequence tasks (Hardwick et al. 2013) – but the more recent Spampinato et al. review (2021) suggests that the stage and mode of learning might be greater determinants of the primary cortical networks involved than the nature of the skill itself.

Human behaviour is a complex phenomenon that is affected by many complicated factors such as memory, motivation, and attention (Kantak & Winstein 2012), and the effects of motivation and attentional focus on motor learning and performance are getting increasingly harder to ignore – autonomy support, enhanced expectancies and external attentional focus have been shown to enhance success in both skill learning and performance (Lewthwaite & Wulf 2017). Animal studies have shown the blocking of dopamine receptors of the motor cortex or lesioning the cortical dopaminergic pathways to impair both LTP and motor skill acquisition, indicating a direct role of dopaminergic pathways and dopamine receptors in motor learning (Spampinato & Celnik 2021), suggesting motivation to play a role beyond merely facilitating the continuation of practice. Reviews on learning and stress show that acute stress can be either helpful or harmful for learning and memory (Vogel and Schwabe 2016; Shors 2016), while chronic stress is shown to be generally more harmful (Roozendaal 2009; Castañeda et al. 2015).

2.2 Neurophysiological processes underlying learning

LTP is generally considered the closest neurophysiological mechanism involved in learning and memory storage (Baudry et al. 2011; Kumar 2011; Shors & Matzel 1997). It was originally discovered at excitatory glutaminergic synapses of the hippocampus of a rabbit by Bliss &

Lomo (1973) and has since been studied in a wide variety of mammalian species and investigated in various brain structures throughout the mammalian central nervous system (CNS), including the cortex, cerebellum, and striatum (Kumar 2011). Different areas of the brain exhibit different forms of long-term potentiationg, the NMDA receptor-dependent and NDMA receptor-independent being the two major types (Kumar 2011). NMDA receptor-dependent LTP has been shown to occur in the cortex (Artola & Singer 1987; Teyler 1989; Jung et al. 1990; Fox 2002; Ziemann 2004; Suppa et al 2016; Brown et al. 2021), cerebellum (Salin et al. 1996; Lev-Ram 2002), and striatum (Calabresi et al. 1992; Lovinger 2010; Lovinger & Kash 2015), and since motor learning requires engagement of plastic processes in these three brain areas (Dayan & Cohen 2011; Penhune & Steele 2012; Caligiore et al 2017), all mentions of LTP in this paper will refer specifically to the NMDA receptor-dependent type. It is important to note, however, that most studies on LTP referenced here have studied hippocampus and memory, not motor cortex and skill acquisition.

2.2.1 Long-term potentiation and synaptogenesis

Inhibitory synapses are mainly located on the somata and shafts of the dendrites, whereas excitatory synapses are typically associated with dendritic spines (Kreienkamp & Dityatev 2004). Although the formation of inhibitory synapses is likely to play a role in skill acquisition, the larger focus of this sub-chapter is directed at LTP of excitatory synapses and the underlying changes in the structure of dendritic spines. Some models divide the stages of LTP into generation, stabilization, consolidation (Rudy 2015) and maintenance (Kwapis & Helmsletter 2014; Hsieh et al. 2017), while others divide them into initial LTP, early LTP and late LTP (Kumar 2011). The synaptic changes in LTP evolve in overlapping stages, yet temporally distinct stages (Rudy 2015). Note that most studies on LTP referenced here, including those on time course, have been done on hippocampus, and at least one study by Teyler (1989) has shown the time course of LTP to be slower in the neocortex than hippocampus. A review on learning-performance distinction by Kantak & Winstein (2012) describing the stages and time courses of motor memory formation also suggest the processes related to motor skill acquisition to be slower than that described in the referenced hippocampal studies (Kantak & Winstein 2012).

LTP generation occurs when glutamate, the first messenger, released from the post-synaptic membrane of the presynaptic cell binds to GluA1 AMPA receptors and to NMDA receptors of the post-synaptic cell, after which influx of sodium ions depolarizes the post-synaptic cell and the magnesium-plug is removed from the NMDA receptors, allowing calcium-ions, the second messenger, to flow into the post-synaptic cell, following their electrical gradient through the open NMDA receptors. The rising level of calcium ions activates calpain, a protease that degrades spectrins, thereby depolymerizing actin and altering the structure of the dendritic spine to allow more AMPA receptors to the post-synaptic dendrite. Calcium ions also activate protein kinases that contribute towards trafficking and trapping additional GluA1 AMPA receptors to the post-synaptic dendrite. The combination of these processes increase response to glutamate. (Baudry et al. 2011; Rudy 2015)

LTP stabilization occurs over several minutes and requires reorganization of the subsynaptic actin cytoskeleton (Baudry et al. 2011). Actin repolymerizes to fix the shape of the dendritic spine (Baudry et al. 2011; Rudy 2015) and cell-adhesion molecules align and stick the pre- and post-synaptic cells together (Huntley et al. 2002). If actin polymerization is disrupted during this stabilization period, the connection is terminated – the actin cytoskeleton shrinks, potentiated synapses de-potentiate, and the potential memory is lost (Rudy 2015). It's been suggested that some signalling pathways involved in LTP generation and stabilization, namely calpain activation through ERK-mediated phosphorylation, could both terminate the stabilization sequences and set in motion processes leading to and required for later stages of consolidation (Baudry et al. 2011). Acute stress has been shown to influence dendritic spine density in one way or the other, depending on a couple of factors such as the type of the stressor and sex of the subject (Shors 2016) – it can be either helpful or harmful. Chronic stress, however, has been shown to have a degrading effect on dendritic spines via disruptions in cell-adhesion (Castañeda et al. 2015), essentially weakening or breaking the connections.

LTP consolidation occurs in 2–4 hours and requires protein synthesis in dendrites (Bramham & Wells 2007; Won & Silva 2008). Some of the required mRNA already exists in the dendritic spine, and transcription of more in the nucleus of the post-synaptic cell is initiated by phosphorylation of transcription factors occurring via synapse-to-nucleus and soma-to-nucleus (Bramham & Wells 2007). BDNF released from the presynaptic axon terminal binds to TrkB receptors in the post-synaptic cell, regulating the activity of mTOR-TOP pathway, leading to efficient protein translation on the post-synaptic cell (Elmariah et al. 2004). Immediate early genes translated rapidly in response to strong synaptic activation include Arc, which helps maintain cofilin phosphorylated hence promoting actin polymerization, a key mechanism in maintaining the enlarged spine formation (Messaoudi et al. 2007; Bramham et al. 2008).

Ubiquitin proteasome system modulates LTP: in early phases of LTP induction it limits potentiation by degrading proteins already present in the dendritic spine, whereas in later stages it promotes translation of new proteins by degrading transcription regressors in the dendrite (Hedge 2010).

Maintenance of LTP is a long-term process which seems to require PKMZeta, a persistently active protein kinase that helps release and trap GluA2 AMPA receptors to the post-synaptic dendrite (Kwapis & Helmsletter 2014; Hsieh et al. 2017). Persistent PKMZeta increases have been shown to coincide with the strength and duration of memory retention (Hsieh et al. 2017), suggesting this to be among the mechanisms behind long-lasting, practically permanent memories. Retrieval trials been shown to have the capacity to render stable memories labile via a process termed reconsolidation (Kwapis et al. 2017). New, relevant information presented during retrieval presumably triggers destabilization of the old memory trace, allowing for modification, but when retrieval includes only familiar information, the memory remains relatively stable and resistant to amnesic events (Kwapis et al. 2017). This mechanism could, in part, explain the relative permanence and stability of automatic skills as well as the role of intentional variation in modifying learnt skills.

2.2.2 Metabolic changes in the central nervous system

Metabolic changes in the central nervous system include acute changes like the changes in viscosity due to water content change (Sanes & Donoghue 2000) and chronic changes like angiogenesis – the formation of new blood vessels (Kerr et al. 2010). The plastic cellular changes of the central nervous system also include increases in conduction velocity due to changes in myelin content (Fields 2015). The exercise-induced metabolic changes are specific to the area activated by training – more changes are seen in the motor cortex than in the frontal cortex or subcortical structures (Swain et al. 2003). The benefits of exercise for learning and memory in general are partly due to exercise-induced angiogenesis (Adkins et al. 2006). While skill training is currently thought to be the only training modality to elicit significant changes in motor cortical circuitry, endurance and resistance training might act as essential nutritive support by increasing vasculature (Adkins et al. 2006).

While the synapse has generally been the main focus of theory on the neurophysiological mechanisms of nervous system plasticity and learning, the consideration of plasticity has recently expanded into other mechanisms beyond the synapse, notably including the distinct possibility that conduction velocity and therefore timing of information transmission could be modifiable through changes in myelin. Synaptic activity across complex neural circuits and networks includes oscillatory elements and requires high accuracy and precision, highlighting the effect localized alterations in conduction velocity can have. Myelination can be influenced by functional activity, but whether this is a homeostatic response to overall neural activity of a circuit or specifically a learning-driven modification remains to be seen. Oligodendrocytes – the myelinating glial cells have ion channels, neurotransmitter receptors, and membrane receptors for a wide range of growth factors, which could provide a possible mechanism for highly specific, activity dependent regulation of myelinisation. There is emerging evidence linking myelinisation to many types of learning but since myelinisation and myelin is less studied and more complex than synaptogenesis and synapse, drawing strong conclusions would be premature. (Fields 2015)

2.2.3 Spinal cord plasticity

Like the brain, the spinal cord has been shown to adapt with great specificity throughout the lifespan (Wolpaw 2007) and in response to training, although the relative proximity of the spinal circuitry to the outer world and the external reality may demand a more rigid organization compared to the highly flexible cortical circuits with greater momentary adaptability (Christiansen et al. 2017). The alterations of spinal cord reflexes in response to motor training have been shown to be highly task-specific (Adkins et al. 2006) and to play a role in standardizing locomotion on specialized skills like dancing (Wolpaw 2007). The spinal level changes alter and regulate sensory feedback mechanisms and affect task performance (Nielsen & Cohen 2008). Plastic changes in the human spinal cord include changes in spinal reflex properties (Adkins et al. 2006) and can be caused by descending input from the brain, afferent input from the peripheral structures, or sensory supraspinal integration (Christiansen et al. 2017). The task-specific spinal level changes have been shown to occur in relation to cortical changes (Nielsen & Cohen 2008; Christiansen et al. 2017). The brain and the spinal cord are inter-connected circuitries and – especially in the context of motor learning – examining one without acknowledging the role of the other would be excessively reductionistic. Maturation and experience shape the spinal cord to act as a mediator between volition and external reality, a role equally important to any supraspinal processes. (Christiansen et al. 2017)

2.3 Skill decay and retention

Skill decay refers to the loss of performance related to acquired skills after periods of nonuse. It is affected by several factors, such as the length of the nonpractice period, the degree of overlearning, certain task characteristics, methodology of testing, training methods, and individual differences. The single most important determinant to retention of both skills and knowledge appears to be the degree of overlearning. (Arthur et al. 1998; Ward et al. 2012) Other significant factors in skill retention include by individual differences, conditions of the practice, and motivation (Arthur et al. 1998; Ward et al. 2012). In the review articles of both Arthur et al. (1998) and Ward et al. (2012) individual differences refer to the notion that higher ability individuals tend to retain more knowledge and skills over periods of nonuse than lower ability individuals – essentially describing an effective use of cognitive strategies as described by Spampinato & Celnik (2021), or a particularly adept utilization of metacognitive processes. Both Arthur et al. (1998) and Ward et al. (2012) attributed the role of motivation as an indirect factor that affects skill acquisition by influencing the amount of training, but the more recent review by Spampinato & Celnik (2021) indicates that motivation may have a more direct effect in neurophysiology of learning. Skill decay has been shown to be greater when the retrieval conditions differ from those of initial acquisition (Arthur et al. 1998).

One obvious approach to mitigating skills decay is to manipulate methodological factors known to influence retention. Since the two most important factors in skill retention – the degree of overlearning and the individual ability – both have to do with the amount of initial skill and knowledge acquired, designing appropriate skill acquisition interventions is a key factor in retention. (Ward et al. 2012) Despite having a slower acquisition time, variable practice and the incorporation of desirable difficulties have been shown to improve both retention and transfer of skills (Kantak & Winstein 2012; Ward et al. 2012; Healy et al. 2014).

A review by Healy et al. (2014) suggests that – given the effectiveness of meta-cognitive processes and the usefulness of well-planned, strategic use of knowledge and skills the trainees already possess – the introduction of an appropriate combination of declarative and procedural information about the task, along with utilization of external focus of attention can help ensure both strong generalizability and durability of the learnt material (Healy et al. 2014). Furthermore, new material that is presented should be neither too difficult nor too easy, to fit the optimal zone of learnability (Healy et al. 2014). Since individual aptitude and high ability factor strongly in the acquisition and retention of skills (Arthur et al. 1998; Ward et al. 2012), developing generalizable knowledge and skills may be beneficial for subsequent skill training. While overlearning reflects high levels of acquisition that is resistant to interference and decay (Arthur et al. 1998; Ward et al. 2012), the diminishing returns of extra practice should be considered when determining the proper amount of training (Healy et al. 2014).

The duration of the nonpractice period, while having been widely cited as a powerful factor in skill decay may in fact operate through mechanisms other than time per se (Arthur et al. 1998). Skill decay seems to be more a matter of interference than forgetting of information and processes over time (Ward et al. 2012), and physical skills seem to be more resistant to decay than cognitive skills (Arthur et al. 1998). Nonetheless, the duration of the nonpractice interval is among the chief issues to consider, as shorter nonpractice intervals can lead to better retention (Ward et al. 2012). Similarity of testing and training conditions also factors here, since similar conditions provide cues that enhance retrieval of information during the retention assessment (Ward et al. 2012).

3 THE SKILL OF HAND-BALANCING

Handstand refers to an inverted stance with hands serving as the sole base of support (Wyatt et al. 2021). In artistic gymnastics the static form of a handstand serves as an initial and/or final position of many movement elements, whereas the dynamic form is either the basis or a component of more complex elements. (Arnista et al. 2020) Learning and developing the postural control related to skilled hand-balancing depends primarily on the integrated function of the vestibular, proprioceptive, and nervous systems (Gautier et al. 2007; Hedbávný et al. 2013a; Olchowik et al. 2015; Omorczyk et al. 2018), highlighting the importance of sensorimotor integration and the use of senses. Vision plays an important role in balancing but is not strictly necessary in the case of expert gymnasts (Gautier et al. 2007). More experienced gymnasts have been shown to minimize both anterior-posterior and medial-lateral body sway by exerting more force on the floor surface (Omorczyk et al. 2018; Sobera et al. 2019).

3.1 Different balance strategies

Keeping the body in a static position is an inapparently dynamic process of continually recreating balance by corrective movements, during which a hand-balancer can utilize several strategies prioritizing the contribution of different joints (Hedbávný et al. 2013a). Analogous to how postural sway in upright position can be managed by ankle, knee and hip strategies, hand-balancer can utilize wrist, elbow, shoulder, or hip strategies (Kerwin & Trewartha 2001). Studies on different balance strategies in handstand of a level floor suggest the wrist strategy and shoulder strategy to be more effective than the hip strategy (Hedbávný et al. 2013a; Rohleder & Vogt 2018). A study by Kochanowicz et al. (2018) examining muscle activity and the contributions of different muscles to postural control in hand-balancing on a level floor found that wrist flexors and trapetzius descendens provide the greatest contribution, followed by anterior deltoid and triceps brachii (Kochanowicz et al. 2018). The importance of the wrist joint in handstand is further supported by studies showing better learning and/or performance outcomes when the wrists are specifically addressed either by explicit instruction (Rohleder & Vogt 2019) or by elastic taping (Vinken & Heinen 2015). A recent study by Calderón-Díaz et al. (2021) examining Chilean circus athletes suggests that the more asymmetrical and challenging the position, the greater number of balance strategies emerge to maintain the given posture (Calderón-Díaz et al. 2021).

Biomechanical examination of handstand on different gymnastics apparatuses has found the balance strategy of experienced gymnasts to be relatively similar on the floor and on the parallel bars, yet on the still rings the balance strategy is notably different – relying significantly more on the shoulder joint and less on the wrist. (Kochanowicz et al. 2019) The authors of the study attributed the difference mostly to the fixed wrist position on the still rings (Kochanowicz et al. 2019), yet another possible factor is the difference between aligning the center of mass on the base of support and aligning the base of support under the center of mass. The movement of center of mass and center of pressure seems to be causally driven, and more skilled hand-balancers have demonstrated greater adaptability by use of reactive – instead of anticipatory – control strategies, highlighting the adaptability of the motor control system (Wyatt et al. 2021).

3.2 Prerequisite strength and flexibility

A high-level performance of handstand – especially the gymnastic-variation often considered the “correct form” – involves adequate strength of arms which carry the whole hand-balancer’s weight, while actively controlling the shoulder girdle and space orientation (Hedbávný et al. 2013b). Several studies like Hedbávný et al. (2013a), Omorczyk et al. (2018) and Sobera et al. (2019) vaguely state how the skill of handstand requires strength, and EMG-studies on static handstand suggest that hand-balancing on a level floor specifically requires strength of the wrist flexors, trapetzius descendens, anterior deltoid and triceps brachii (Kochanowicz et al. 2018), though direct evidence on correlation between strength levels and hand-balancing performance seems to be limited to one study by Hedbávný et al. (2013b).

A study on gymnasts by Hedbávný et al. (2013b) examining the correlation between upper extremity strength as measured by the number of push-ups in a minute and static handstand performance found a strong dependence between strength and handstand performance ($r = 0.718$ and $p < 0.0003$ for maximal time, $r = -0{,}6989$ and $p < 0.0006$ for quality of performance). Strength in the corresponding muscle groups can be a limiting factor, and hand-balancers with better strength abilities may dare do corrective movements in bigger extent (Hedbávný et al. 2013b), indicating that higher strength abilities allow for more freedom in choosing balance strategies. Hedbávný et al. (2013b) mainly attributed the correlation of strength and skill to the notion that stronger gymnasts also perform better. However, mirroring their results against Spampinato & Celnik review (2021) on skill acquisition suggests that higher strength may allow for greater corrections, allowing hand-balancers to “get away with” bigger fluctuations, thus facilitating progression from error-based learning towards reinforcement learning.

On still rings the relative contribution of the wrist joint is reduced and the role of anterior deltoid and latissimus dorsi are greatly increased, indicating both a notably higher difficulty level and significantly higher strength requirements (Kochanowicz et al. 2019). The role of triceps brachii in handstand on all apparatuses seems to be to fix the elbow joint to allow for more effective use of wrist- and shoulder strategy (Kochanowich et al. 2019). A Mizutori et al. study on straight-arm pike press to handstand (2021) showed that in addition to demands in the strength of the anterior deltoids, trapetzius descendens and the wrist flexors, pike press to handstand requires active pike compression flexibility of the hip joint (Mizurori et al. 2021).

4 PERIODIZATION

The human body responds to different stressors in a wide spectrum of adaptations ranging from highly beneficial to ill-adjusted (Cunanan et al. 2018). Neurobiological organisms are best described as complex and nonlinear phenomena exhibiting chaotic and sensitive dependent properties in vastly divergent emergent outcomes (Afonso et al. 2020), yet considerable evidence shows that periodization – a methodological attempt to manage training adaptations logically and predictably – can reliably produce greater performance adaptations compared to non-periodized methods (Stone et al. 2021). Exercise periodization aims to properly sequence and distribute training load and content across pre-established cycles (Afonso et al. 2020; Stone et al. 2021) to achieve desired adaptations via a planned combination of training load and rest (Cunanan et al. 2018). This sequencing presupposes that certain order and timing for the application of stimuli may promote better-adjusted adaptations than others, and predicts what inputs lead to intended outputs (Issurin 2008; Naclerio et al. 2013). The foundation of periodization is built on the understanding of training adaptations, residual effects, decay rates and non-compatible fitness factors (Stone et al. 2021).

Periodization for sport has been criticized (Kiely et al. 2012), but as Stone et al. succinctly pointed out in their review (2021), the arguments made against periodization are based mostly on misconceptions, such as misunderstanding the conceptual nature of periodization, misunderstanding the underlying mechanisms driving adaptation, confusing programming with periodization, the use of inefficient programming methods to drive the selected periodization model, and failure to recognize the developmental history of these factors (Stone et al. 2021). In several studies block periodisation has been documented as superior to other periodisation models (Painter et al. 2012; Rønnestad et al. 2019; Stone et al. 2021). Conceptually, block periodization is the act of managing timelines and creating logical training stages consisting of distinct training phases/blocks: accumulation phase, transmutation phase, and realization phase. The continuum from accumulation to realization via transmutation phase aims to ensure long-term progress and limit unnecessary training load by relying on what is known about training adaptations, residual effects and compatibility of different training modalities. (Stone et al. 2021)

As far as strength, power or endurance goes, periodization of physical training has been studied extensively (Plisk & Stone 2003; Lyakh et al. 2016; Stone et al. 2021). Data on training volumes and intensities needed for improvement versus maintenance exists (Bickel et al. 2011; Macpherson & Weston 2015; Iversen et al. 2021), and the effect of detraining has been studied as well (Bosquet et al. 2013; Sousa et al. 2019). Extensive body of literature on behavioural and neurophysiological adaptations to motor skill training exists (Spampinato & Celnik 2021), yet periodization of physically demanding motor skills has not been studied (Farrow & Robertson 2017). Some evidence on permanence of skills suggests that provided an effectively executed skill acquisition phase, a following nonpractice period has no negative effect on performance of the acquired skills (Arthur et al. 1998; Ward et al. 2012; Spampinato & Celnik 2021), indicating how a residual effect of a properly executed skill training block could work.

4.1 Block periodization for performance in sports

Sports performance is a complex, multifactorial phenomenon, and in some sports the highest peak performance can only be maintained for some days. Periodization, when appropriately programmed, allows coaches, sport scientists and practitioners to qualitatively predict – and to some extent cause – the occurrence of the desired performance peak. Periodization deals with the macromanagement of training and deals with timelines, fitness phases and continuums from general to specific, whereas programming deals with week-by-week, day-by-day, and session-by-session micromanagement of training variables within the training phases. (Stone et al. 2021) While several periodization models have proved effective in increasing strength or power, block periodization, when appropriately programmed, has been shown to be superior to other models (Painter et al. 2012; Stone et al. 2021). Periodization deals with strategic manipulation of variables around specificity, progression and functional overload to ensure long-term gains (Farrow & Robertson 2017; Stone et al. 2021).

The primary premise of block periodization is appropriately planned sequencing of concentrated training phases in logical order to benefit from the emergent residual effects of training. Block periodization consists of three periodization blocks – accumulation, transmutation, and realization phase – which together make up a stage. Evidence indicates that when properly programmed, each periodization block results in foundation-laying residual effects that persist for a time, potentiating the next block. Two variations of block periodization exist: single factor and multi-factor, depending on the amount of simultaneous primary goals. Training load and fatigue management is a key element of block periodization: focusing on one or few fitness factors at a time provides adequate training stimulus for that factor without accumulating fatigue due to excessively high training volumes or interference due to incompatible fitness factors. Block periodization, together with numerous programming schemes allows for individualization, autoregulation and a substantial amount of flexibility to adjust for the complexity of reality. (Stone et al. 2021)

Accumulation phase serves to potentiate the next block. Generally, the accumulation block focuses on fitness factors that serve to build a general foundation to support the more specific elements of the sport, for example general strength and hypertrophy to support speed and power, or endurance to support general work capacity. The duration and content of the accumulation phase depend on the level, situation and goals of the athlete. For example, a mediocre basketball athlete could spend five weeks accumulating endurance, whereas an elite level athlete could spend two weeks on it. The accumulation phase is followed by the transmutation phase, where sport specific skill training begins to increase, and the exercise selection of strength training becomes more sport specific. Transmutation phase is followed by the realization phase. Realization phase begins with planned overreaching, where strength training once again briefly predominates. Exercise selection become increasingly more task specific and training volume decreases towards and during the taper portion of realization phase. (Stone et al. 2021)

4.2 Detraining

Residual effects of training and decay timelines with non-use of specific training differ across different physiological adaptations. Some neural adaptations related to improved coordination and general movement skills last years, certain cardiovascular and neuromuscular adaptations last months, and some bioenergetic adaptations last weeks. (Stone et al. 2021). Age affects the rate of strength decay, yet even with the decreases in strength with advancing age, older untrained individuals respond well to strength training and maintain the gains of a strength block over 12 weeks of time. Gender does not seem to affect the rate of strength decay with detraining. (Lemmer et al. 2000)

Prolonged periods of detraining regarding strength demonstrably lead to both strength loss and atrophy (Bosquet et al. 2013; Sousa 2019), with muscular training adaptations reversing to greater degree than neural adaptations (Lemmer et al. 2000). Strength and muscle mass can, however, be maintained by even small doses of training, as demonstrated by several studies showing a short training session performed once a week to be adequate in maintaining maximal strength and hypertrophy, with muscular adaptations requiring slightly more training volume than maximal strength (Iversen et al. 2021). Bickel et al. study (2011) comparing maintenance protocols of three sets per exercise once a week vs. one set per exercise once a week in older vs. younger subjects found that young subjects maintained both strength and hypertrophy with either of the maintenance protocols, while older subjects successfully maintained strength with both, but hypertrophy only with the protocol involving three sets per exercise (Bickel et al. 2011).

4.3 Periodizing skill training

Knowing the effects given training modalities have on subsequent detraining periods is key in understanding how to design periodization plans and training programs to optimize performance and mitigate performance losses (Sousa et al. 2019). While skill acquisition literature provides a range of principles that may guide effective skill development, skill acquisition does not currently utilize a periodization model to plan, monitor and evaluate programs (Farrow & Robertson 2017). The general logic of periodization for strength and power usually goes from general to specific, from higher volume towards lower volume, and from lower intensity to higher intensity (Stone et al. 2021). An investigation of the interactions of individual constraints with task constraints to determine how specific training needs to be would follow a similar kind of logic (Farrow & Robertson 2017).

Since highly generalizable fundamental skills serve as building blocks for more advanced skills (Logan et al. 2017) and reviews on skill retention have shown initial individual ability and aptitude to be a major factor in skill acquisition and retention (Arthur et al. 1998; Ward et al. 2012; Healy et al. 2014), building from general sensory-motor skills and meta-cognitive attributes towards more representative skills could be productive for long term skill acquisition. Somewhat analogous to increase in intensity of strength training, the increased representativeness could in some cases be accompanied by increase in psychological load, for example when a rock-climbing task takes place notably higher from the ground (Farrow & Robertson 2017).

Block periodization for strength and power ensures progression over time by using focused training phases to build upon the residual effects of previous training phases (Stone et al. 2021). There are many ways to define progression in skill-training context. In addition to the obvious metric of improved skill performance in the desired environment, progression of skill may also be considered in terms of the capacity to tolerate an increased skill practice load, as represented by greater technical demand, increased practice trial volume, higher practice representativeness, and/or increased mental exertion. Skill training load could be estimated by a method similar to the largely subjective session RPE method. (Farrow & Robertson 2017)

The strategic use of planned overload in periodization models of strength and power has been used to elicit specific adaptations at desired times (Stone et al. 2021). For skill training, the concept of monitoring and adjusting for internal training load and external training load, is readily importable from the domain of physical training. Especially contextual interference from skill acquisition literature lends itself to this – early on in training increasingly blocked, low mental effort training might be prioritized, whereas later in training the weight shifts towards more mentally strenuous random-order training, where increased mental load is accompanied by increased skill acquisition and retention. (Farrow & Robertson 2017) This order of skill training is in line with the different learning styles as described by Spampinato & Celnik (2021) in their review on neurophysiological bases of motor learning.

Accounting for reversibility is a crucial tenet of periodization – one must understand residual effects and the decay timelines of different physical adaptations in order to effectively account for them (Stone et al. 2021). The enhanced retention brought about by intentional difficulties in learning such as variable practice and contextual interference (Kantak & Winstein 2012; Ward et al. 2012; Healy et al. 2014) could be viewed as analogous to residual effects of a successful accumulation phase as described by Stone et al. in their recent review (Stone et al. 2021). As reviews on skill decay and retention show that the nature of training influences retention more than the nature of the skill training break (Arthur et al. 1998; Ward et al. 2012) and evidence on neurophysiological processes underlying learning describe plausible mechanisms for the generation and maintenance of permanent skills (Kwapis & Helmsletter 2014; Hsieh et al. 2017), a total break in skill training might not be detrimental if the acquisition is done appropriately.

5 PURPOSE OF THE STUDY

The methodology of learning and retention seems to influence skill decay more than time from learning (Arthur et al. 1998; Kantak & Winstein 2012; Ward et al. 2012). The most important factors influencing retention include initial aptitude, motivation, the degree of overlearning (Arthur et al. 1998; Ward et al. 2013), and practice conditions (Kantak & Winstein 2012; Haley et al. 2014).

The hypothesis is that if a) the skill is learnt with variable practice emphasizing error-based and reinforcement learning, b) the skill training is logically periodized, and c) the physical prerequisites are maintained, training break has no negative effect on skill acquisition.

Research question 1: Does a 2-week long break in skill-training affect learning outcomes?

Hypothesis: No. While some studies have found superior results in skill acquisition with 12 versus 10 weeks of training (Cabral et al. 2019), reviews on skill retention suggest that the methodology of learning is more influential than the duration of the non-training period (Arthur et al. 1998; Ward et al. 2013). Furthermore, the literature around neural adaptations related to learning suggests that adequately consolidated neural connections are maintained for longer periods of time than the present training break (Kwapis & Helmsletter 2014; Hsieh et al. 2017).

Research question 2: Does timing of the training break affect learning outcomes?

Hypothesis: Yes, for the first mid-measurement, no for the whole intervention. By the first mid-measurement the difference of training handstands 5 vs. 7 weeks is significant, but by the end of the intervention the difference will have disappeared. Furthermore – the strength training phase might theoretically even potentiate the upcoming skill training phase, yielding greater results for groups B and C, but neither the length of the strength training phase nor the intervention itself is long enough to show meaningful differences.

Research question 3: Is motor learning linear during the training intervention?

Hypothesis: No. Several studies have shown motor learning to be non-linear (Dayan & Cohen 2011; Schöllhorn et al. 2012), and the variable practice shown here adds to the non-linearity.

Furthermore, properly periodized training includes training phases that build foundational elements in a way that potentiates the next training phase but doesn’t necessarily show immediate sport-specific performance improvements (Stone et al. 2021).

Research question 4: Is there a correlation between initial general pushing strength and progress in handstand performance tests?

Hypothesis: Yes. Strength of the wrist flexors, trapetzius descendens, anterior deltoids and triceps brachii is thought to be a prerequisite for successful handstand practice (Hedbávný et al. 2013a; Omorczyk et al. 2018; Sobera et al. 2019), and at least one study has found a direct correlation between push-up repetition maximum and handstand performance (Hedbávný et al. 2013b). Due to force production requirements of different balancing strategies, strength is thought to be more important for balancing than form, yet it is expected to correlate with both.

6 METHODS

The training intervention was a 13-week progressive online handstand course with pre-, mid-, and post-tests performed at six points. Subjects were recruited during January 2021, the training intervention took place between 2/2021–5/2021, and data-analysis was performed between autumn of 2021 and summer of 2022. Due to covid-restrictions of early 2021 all communication with the subjects was done remotely and all training sessions and measurements were done via recorded videos in a way that allowed the subjects to complete all training sessions and measurements in their own homes.

6.1 Subjects

Recruitment was done by using social media and contacting gymnastics and circus clubs via email. The target group was 18–60-year-old healthy people who were initially able to rise into wall-assisted handstand facing the wall but were unable to hold a freestanding handstand for more than one minute. 511 participants were initially recruited, and subsequently divided randomly into three groups. After the inclusion criteria was set at attending a minimum of 80 % of total training sessions along with pre- and post-measurements fully completed, the final number of subjects was n = 41. The final group sizes were – coincidentally – similar between groups: group A had 13 subjects, whereas groups B and C had 14 subjects each. The study was approved by the ethics committee of the University of Jyväskylä (1756/13.00.04.00/2020).

6.2 Study design

The training intervention included 2 approximately 45-minute video-instructed follow-along training sessions per week for 13 weeks, with handstand measurements performed at weeks 0, 5, 8, 10, and 13, and strength measurements performed at weeks 0 and 13. All three groups performed 2 training sessions each week, but the content of training sessions differed, with one group training handstands for 13 weeks and two groups training handstands for 11 weeks and upper-body strength for 2 weeks. Time course of the intervention, along with timings of the skill-training break and all performance measurements are shown in table 1. Thinkific-online platform was used for both the follow-along video sessions and collection of feedback forms, and email was used for collecting the videos and test-results from the subjects.

TABLE 1. Outline of group division and training plan. Mid-tests were performed during normal HS-training sessions after warm-up.

Intervention week	Group A (n = 13)	Group B (n = 14)	Group C (n = 14)
0	Pre-measurements for all groups (HS, strength)		
1	2 HS training	2 HS training	2 HS training
2	2 HS training	2 HS training	2 HS training
3	2 HS training	2 HS training	2 HS training
4	2 HS training	2 HS training	2 HS training
5 – Test at 2nd session	2 HS training	2 HS training	2 HS training
6	2 HS training	**2 STR training**	2 HS training
7	2 HS training	**2 STR training**	2 HS training
8 – Test at 1st session	2 HS training	2 HS training	**2 STR training**
9	2 HS training	2 HS training	**2 STR training**
10 – Test at 1st session	2 HS training	2 HS training	2 HS training
11	2 HS training	2 HS training	2 HS training
12	2 HS training	2 HS training	2 HS training
13	Post-measurements for all groups (HS, strength)		

Block periodization of different skill-elements was used, and the intervention itself was a periodized, progressive handstand course with all elements of hand-balancing present throughout the intervention – safety of practice, stability of shoulder joint, sense and control of body position, and the act of balancing. While all aspects were present throughout the course, the main focus differed during the four phases of the course, with the 1st phase focusing on safety of practice and stability of shoulder joint, 2nd on sensing and varying the position, 3rd on balancing and 4th on integration of different elements around balancing and positional awareness. Periodization plan for the intervention is outlined in table 2.

TABLE 2. Outline for the periodization plan for the handstand training intervention.

Weeks	Main focus	Side focus	Maintenance
1–2	Safety, shoulder stability	Positional awareness	Balancing
3–5	Positional awareness	Shoulder stability	Safety, balancing
6–9	Balancing	Awareness and stability	Safety
10–13	Balancing, awareness	Stability	Safety

The handstand skill-training sessions were instructed from beginning to end, including both the 10–15-minute handstand-specific warm-up and 25–35-minute skill training portion. The main focus of each handstand session was determined by the periodization plan shown in table 2, but the specific exercise selection varied and progressed throughout the intervention. Each specific training session was repeated twice, and as such the intervention included 13 unique handstand training sessions and 2 unique strength training sessions. All skill sessions were planned by Hänninen and Rinnevuori, and strength sessions were planned by Hänninen. The training sessions were filmed by Hänninen and Rinnevuori. Since it was hypothesized that the nature of skill acquisition process plays a part in retention, the 13-week handstand course included variety of different tasks as well as use of external focus.

The 2-week strength training phase included two strength training sessions per week, both of which included one vertical pushing exercise, one horizontal pushing exercise and one core strength exercise, as well as supplementary work on the wrists. A detailed instruction on how to adjust the load via elevated surfaces and weight shifts was provided in the follow along-video, and the subjects were instructed to aim for 3 x 8 at a specific intensity, as specified in table 3. Inter-set rest periods were between 1,5–2 minutes.

TABLE 3. Exercise selection, training protocol and intensity (as Repetitions in Reserve).

Strength sessions 1 and 3.	Strength sessions 2 and 4.	Sets x Reps	Intensity	
			Week 1	Week 2
1. Pseudo-planche push-ups	1. Asymmetric lizard push-up	3 x 8	2–3 RIR	1–2 RIR
2. Bear push-up	2. Asymmetric bear push-ups	3 x 8	2–3 RIR	1–2 RIR
3A. Plank slide	3A. Jack-knife to L-sit	3 x 5	2–3 RIR	1–2 RIR
3B. Wrist push-up	3B. Wrist push-up	3 x 1	2–3 RIR	1–2 RIR
3C: Reverse wrist push-up	3C. Reverse wrist push-up	3 x 1	2–3 RIR	1–2 RIR

6.3 Measurements

Due to covid-related restrictions of early 2021 all measurements were performed via video: The researchers instructed the tests via pre-recorded follow-along videos, and the subjects filmed themselves performing the tests according to the video-instructions. Therefore, all measurements are simple field-tests. All tests were preceded by the same video-instructed warm-up.

6.3.1 Hand-balancing maximum time and qualitative assessment

Subjects were instructed to film themselves performing 3 trials in one take, with each trial starting from a wall-assisted handstand facing the wall. The video was to be filmed from the side with the participant completely in frame. Trials were timed with from the recorded videos with a stopwatch, rounding up to the closest 0.1 seconds. The time starts when the subject leaves the wall and ends when they either touch the wall again, move their hands or hit the floor with their feet.

The longest hold was also assessed qualitatively using criteria based on artistic gymnastics code of points. Assessment criteria are detailed in table 4 and examples of handstand form assessment are shown in figure 1.

TABLE 4. Exercise selection, training protocol and intensity (as Repetitions in Reserve).

Points	Assessment criteria
0	No balance, i.e. less than 1 second hold.
1	Body strongly arched, head tilted back, legs clearly apart, knees bent, or clearly visible corrective movements.
2	Mild shoulder angle, head tilted slightly back, back slightly arched, missing leg extension, legs slightly apart, or small visible corrective movements.
3	Shoulders in full flexion, hollow-body position, head between arms, extended hips and knees, legs together, and no visible corrections while balancing.

FIGURE 1. Handstand form assessment examples. 3 points (left), 2 points (middle) and 1 point (right).

6.3.2 Pushing strength

Strength was tested by repetition maximum of strict-form push-ups under one minute. Handstand performance and strength tests were performed in separate sessions, with strength tests taking place 2–3 days after the handstand performance tests. The strength test was always preceded by the same video-instructed warm-up. Subjects were instructed to film themselves from the side as they performed one set of hollow-body push-ups to failure. Criteria for the push-ups were 1) at the top position arms are extended and vertically aligned with shoulders on top of wrists, 2) at the bottom position the chest touches the ground, and 3) hollow-body position is maintained throughout the set, i.e. the line from shoulder via hip joint to lateral malleolus is straight and doesn't change.

6.4 Statistical methods

Statistical analyses were performed with SPSS software (IBM Corporation, Armonk, NY, USA) and Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). All results are presented as Mean ± SD. Normality of variables was determined by the Shapiro-Wilk test, and since neither pre-, mid- nor post-measurements were normally distributed, Mann-Whitney U-test was used for between-group analyses and Friedmann test was used for analysing within-group differences for the first two research questions. The third research question was analysed by Wilcox test, and the fourth research question was examined with Pearson's correlation coefficient. The threshold for statistical significance was set at $p < 0.05$. Thresholds for very weak, weak, moderate, and strong correlations were set at $r < 0.2$, $r = 0.2–0.4$, $r = 0.4–0.6$, and $r > 0.6$, respectively.

7 RESULTS

Of the 511 participants who started the intervention, 41 completed > 80 % of the training sessions with pre- and post-measurements fully completed, thus meeting the inclusion criteria. The final n = 41. Group A had 13 subjects, and groups B and C had 14 subjects each. Handstand performance level of group A was – coincidentally – significantly higher in pre-measurements ($p < 0.000$ for both qualitative and quantitative measures) compared to groups B and C, but the differences disappeared by post-measurements.

Overall results between pre- and post-measurements. The average handstand balancing time across all groups (n = 41) went from 1.94 ± 4.40 seconds to 6.46 ± 7.88 seconds and the qualitative handstand form (on a scale of 1–3) went from 0.80 ± 0.95 to 1.56 ± 0.59, with no statistically significant between-group differences in balancing time ($p = 0.609$) or handstand form ($p = 0.589$). Progress in balancing time between pre- and post-measurements was statistically significant for each group, and progress in handstand form was statistically significant for both skill-traininb break groups B ($p = 0.011$) and C ($p = 0.001$), but not for the handstand-only group A ($p = 0.059$). Pre- and post-results of all groups are shown in table 5, and pre-, mid- and post-measurements of both handstand metrics are shown in figure 2.

TABLE 5. Pre- and post-measurements of handstand- and strength tests across the intervention.

	Variable	Pre-test	Post-test	p-value
Group A (n = 13)	Balancing time	3.73 ± 7.38	7.35 ± 8.02	0.001*
	Handstand form	1.08 ± 1.12	1.46 ± 0.52	0.059
	Push-up max reps	14 ± 11	15 ± 11	0.058
Group B (n = 14)	Balancing time	0.88 ± 1.03	4.59 ± 4.31	0.001*
	Handstand form	0.64 ± 0.88	1.43 ± 0.51	0.011*
	Push-up max reps	12 ± 12	13 ± 12	0.206
Group C (n = 14)	Balancing time	1.34 ± 1.81	7.51 ± 10.35	0.001*
	Handstand form	0.71 ± 0.91	1.79 ± 0.70	0.001*
	Push-up max reps	17 ± 12	21 ± 12	0.007*
All (n = 41)	Balancing time	1.94 ± 4.40	6.46 ± 7.88	0.000*
	Handstand form	0.80 ± 0.95	1.56 ± 0.59	0.000*
	Push-up max reps	14 ± 12	16 ± 12	0.001*

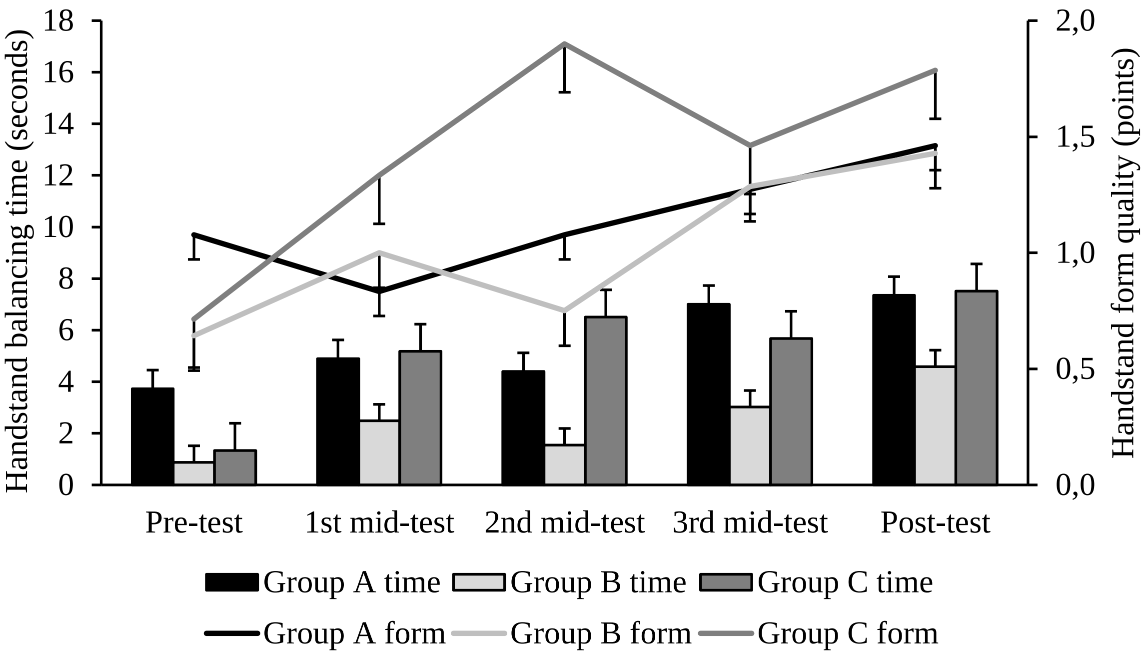

FIGURE 2. Mean values of handstand balancing time (in seconds) and qualitative handstand form assessment (on a scale of 1–3) of each group across the intervention.

The effect of the skill-training break on progress. Comparison between handstand-only group (A) and the combination of skill-training break groups (B+C) showed no statistically significant differences at any of the measurement points, i.e. the skill-training break did not have a significant effect on progress. Improvement in push-up maximum repetitions reached statistical significance for skill-training break groups (p = 0.05), but not for the handstand-only group (p = 0.058). Pre- and post-measurements for the handstand-only group (A) and the combination of both skill-training break groups (B+C) are shown in table 6, and pre-, mid-, and post-measurements of balancing time and handstand form are shown in figure 3.

TABLE 6. Pre- and post-measurements of quantitative handstand balancing time and qualitative handstand form across the intervention.

	Variable	Pre-test	Post-test	p-value
Group A	Balancing time	3.73 ± 7.38	7.35 ± 8.02	0.001*
(n = 13)	Handstand form	1.08 ± 1.12	1.46 ± 0.52	0.059
	Push-up max reps	14 ± 11	15 ± 11	0.058
Groups B+C	Balancing time	1.11 ± 1.46	6.05 ± 7.92	0.001*
(n = 28)	Handstand form	0.68 ± 0.88	1.61 ± 0.63	0.001*
	Push-up max reps	14 ± 12	17 ± 13	0.050*

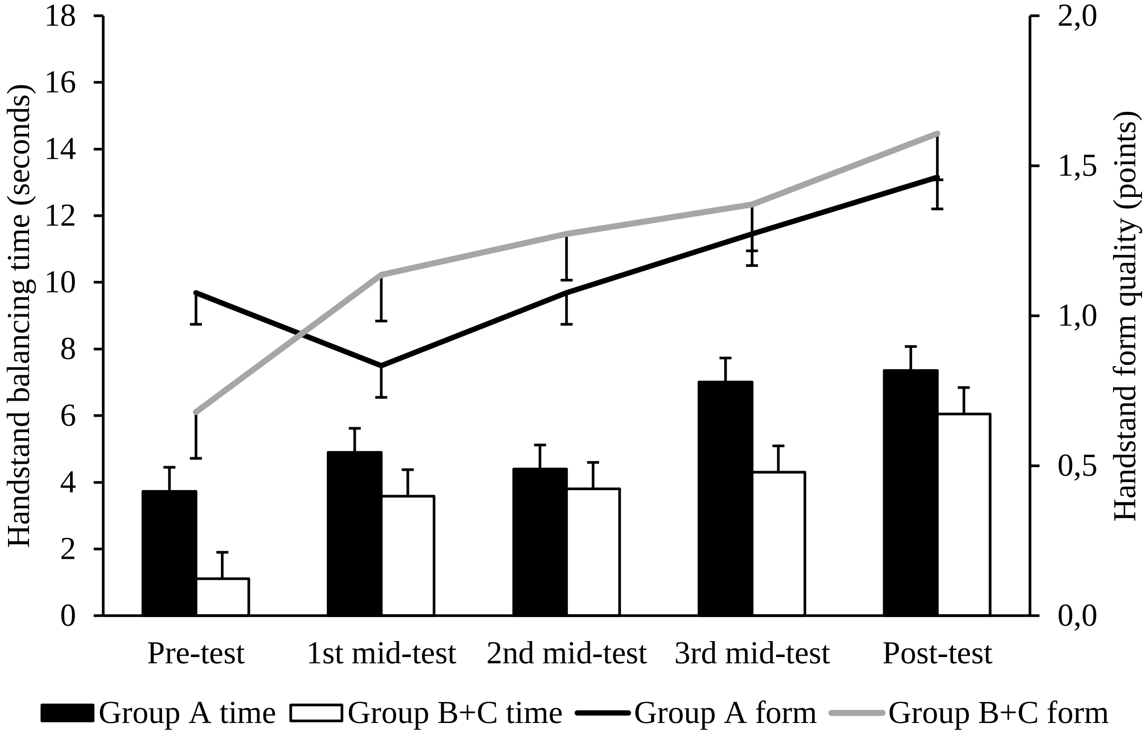

FIGURE 3. Comparison of the handstand-only group (A) and the skill training-break groups (B+C) on handstand balancing time (in seconds) and handstand form (on a scale of 1–3).

The effect of the timing of the skill-training break. As hypothesized, comparison of differently timed skill-training break – early skill-training break group B and late skill-training break group C – showed statistically significant differences associated with the timing of the break at 2nd mid-measurement ($p = 0.001$ for quantitative and $p = 0.004$ for qualitative measurements) in favour of the group who had the break later, but the difference disappeared by later measurements. Comparison between handstand-only group A and late skill-training break group C showed a statistically a significant difference at 2nd mid-test of handstand balancing time ($p = 0.030$), but not for any other variables or measurement points. Comparison between differently timed skill training-breaks is shown in figure 4, and comparison between handstand-only group and the late skill-training break group is shown in figure 5.

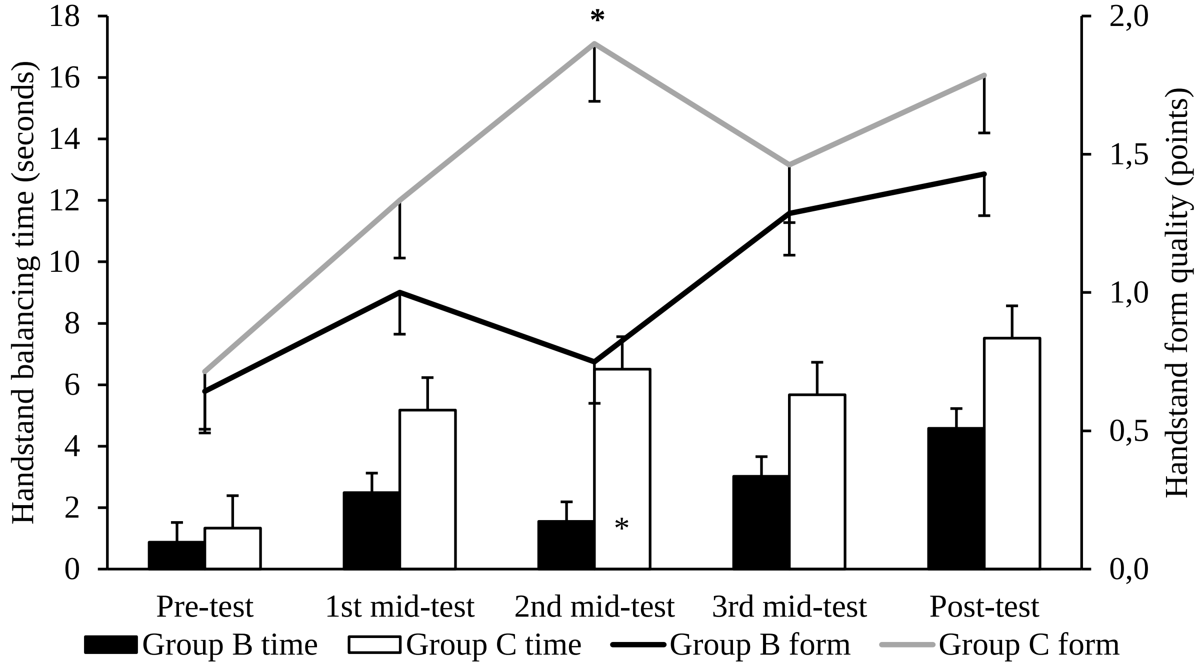

FIGURE 4. Comparison of the skill training-break groups (B and C) on handstand balancing time and handstand form (on a scale of 1–3). Group B had the break between 1st–2nd mid-tests, and group C had the break between 2nd–3rd mid-test.

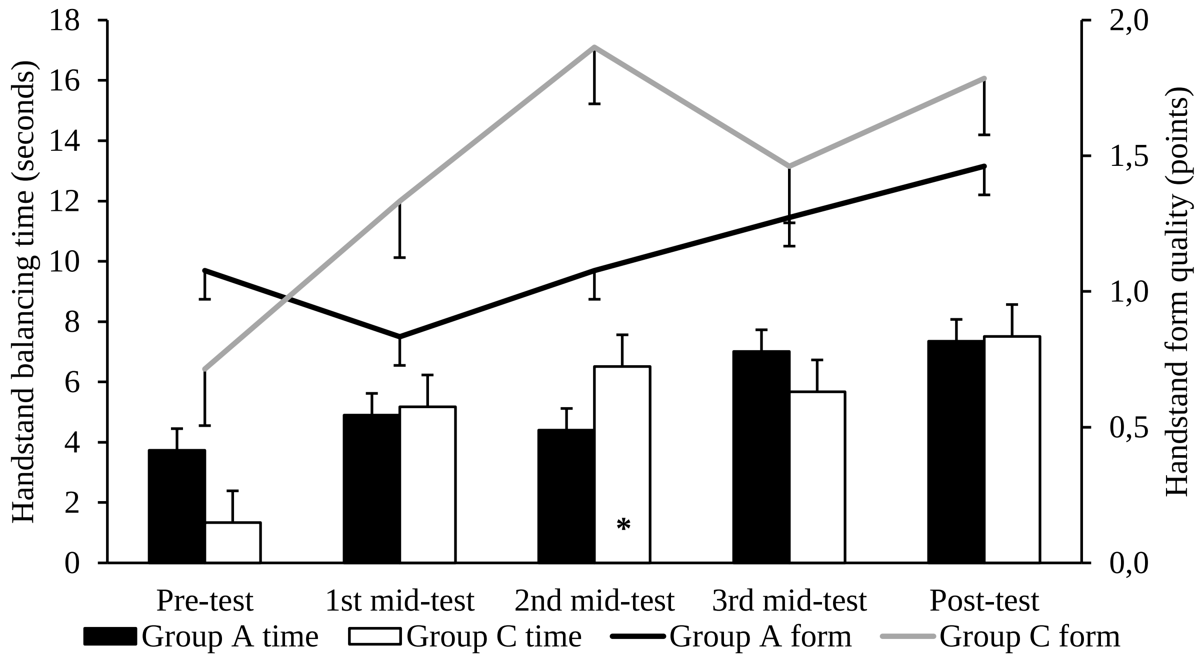

FIGURE 5. Comparison of group A (handstand-only) and group C (skill-training break between 2nd–3rd mid-tests). Training was similar up to 2nd mid-test.

Linearity of progress throughout the intervention. While the improvements in all groups were statistically significant between pre- and post-tests, the improvement throughout the intervention was not linear for any of the groups. The results between consecutive test are shown in table 7 as p-values, and the handstand balancing time measurements and handstand form quality measurements are shown in figures 6 and 7.

TABLE 7. Improvements between consecutive performance tests, shown as p-values.

	Variable	Pre-1st mid	1st-2nd mid	2nd-3rd-mid	3rd mid-Post
Group A	Balancing time	0.035*	0.445	0.080	0.260
	Handstand form	1.000	0.414	0.564	0.157
Group B	Balancing time	0.010*	0.499	0.140	0.182
	Handstand form	0.070	0.564	0.046*	1.000
Group C	Balancing time	0.020*	0.222	0.750	0.414
	Handstand form	0.046*	0.007*	0.257	0.414
All groups	Balancing time	0.000*	0.098	0.070	0.206
	Handstand form	0.003*	0.070	0.593	0.206

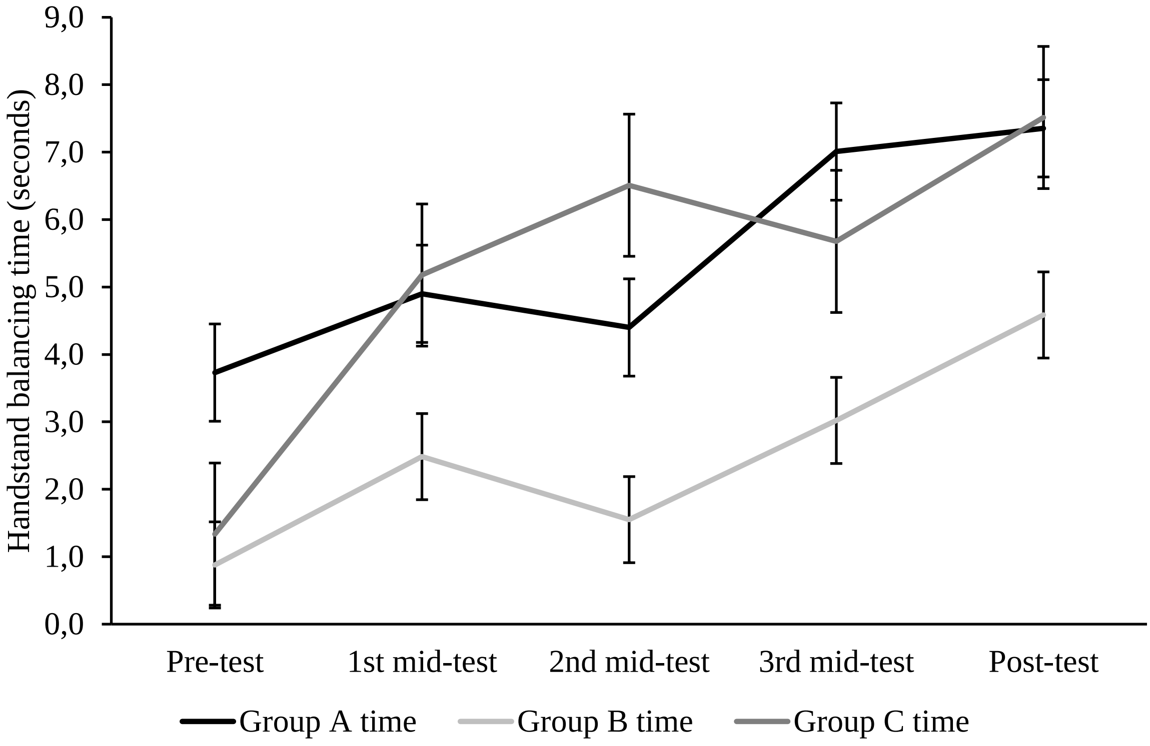

FIGURE 6. Handstand balancing time (in seconds) across the intervention.

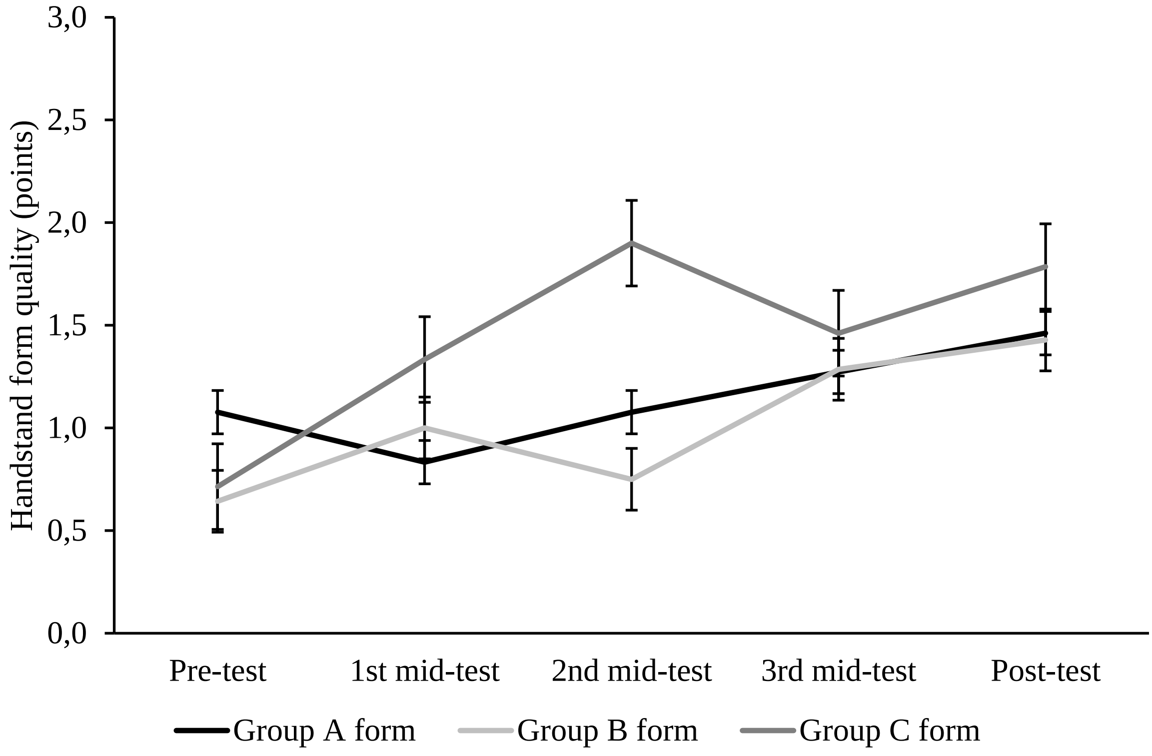

FIGURE 7. Handstand form quality across the intervention on a scale of 1–3.

The effect of initial pushing strength in handstand progress. Across all groups there was very weak correlation with no statistical significance between initial pushing strength and improvement in handstand form ($n = 41$, $r = -0.002$, $p = 0.503$), and a statistically significant moderate correlation between initial pushing strength and improvement in handstand balancing time ($n = 41$, $r = 0.537$, $p = 0.020$). Comparison between handstand-only group A and the skill-training break groups B+C found the correlation between initial pushing strength and improvement in handstand balancing time to be moderate and statistically significant for the skill-training break groups ($n = 28$, $r = 0.554$, $p = 0.018$), but the correlation did not reach statistical significance in the handstand-only group A ($n = 31$, $r = 0.433$, $p = 0.068$). Group C was the only one single group with a strong statistically significant correlation between initial strength level and progress in handstand balancing time ($n = 14$, $r = 0.664$, $p = 0.006$). Correlations between initial strength and improvements in handstand performance markers are shown in table 8, and correlation between initial strength and improvement in handstand balancing time is shown in figure 8.

TABLE 8. Correlations between push-up repetition maximum at the start of the intervention and improvements in handstand performance metrics.

	Initial strength (push-up max reps)	Handstand performance metric	Correlation with strength (r-value)	p-value
Group A (n = 13)	14 ± 11	Balancing time	0.433	0.068
		Handstand form	- 0.204	0.749
Group B (n = 14)	12 ± 12	Balancing time	0.330	0.133
		Handstand form	- 0.160	0.300
Group C (n = 14)	18 ± 13	Balancing time	0.664	0.006*
		Handstand form	- 0.228	0.774
All groups (n = 41)	14 ± 12	Balancing time	0.537	0.021*
		Handstand form	- 0.002	0.503
Groups B+C (n = 28)	15 ± 12	Balancing time	0.554	0.018*
		Handstand form	- 0.055	0.428

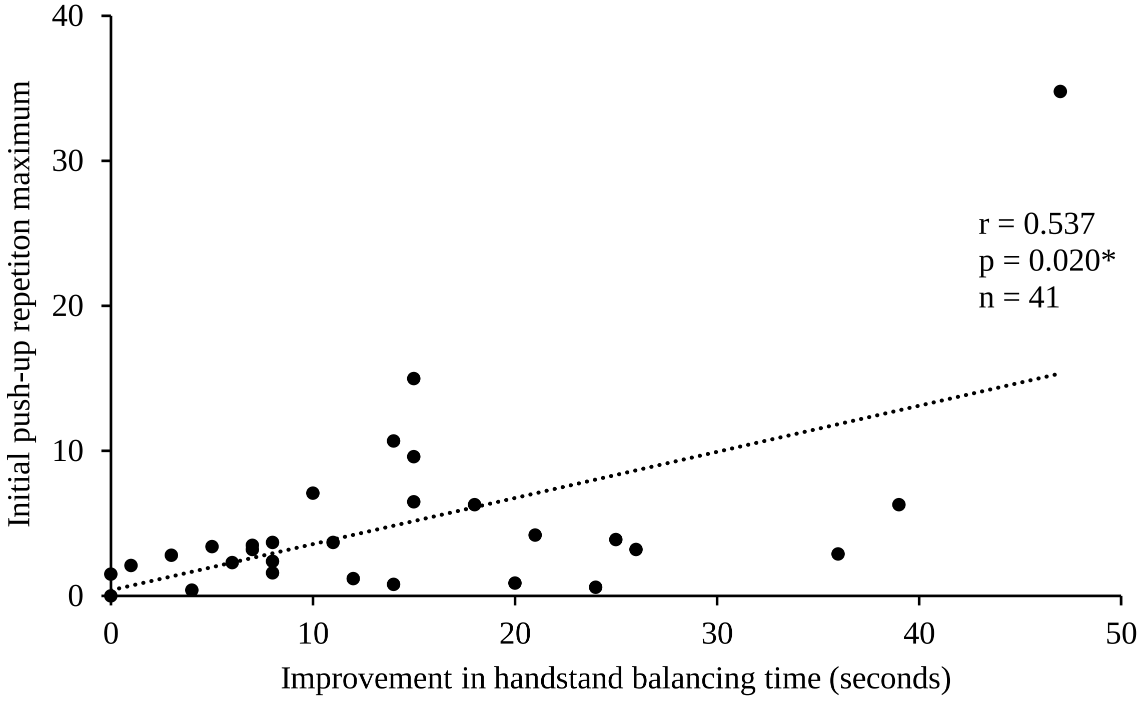

FIGURE 8. Correlation between initial push-up repetition maximum and improvement in handstand balancing time between pre- and post-tests.

8 DISCUSSION

The aim of the present study was to provide insight into periodization of skill training by determining whether the presence or the timing of a skill-training break influences motor learning in a setting where the physical prerequisites of the motor skill in question are trained during the skill-training break. The 13-week intervention measured handstand progress in terms of maximal balancing time and the qualitative handstand form, and the main findings showed that the skill-training break had no negative effect on handstand skill acquisition – and might have been beneficial for it. The average balancing time across all groups ($n = 41$) went from 1.94 ± 4.40 seconds to 6.46 ± 7.88 seconds and the qualitative handstand form (on a scale of 1–3) went from 0.80 ± 0.95 to 1.56 ± 0.59, with no statistically significant between-group differences. Skill retention during a period of non-use has been studied before (Arthur et al. 1998; Ward et al. 2012), but the present study seems to be among the first to examine the phenomenon with respect to a motor skill with a clear strength requirement while successfully maintaining key physical prerequisites during the period of non-use. Previous evidence on skill acquisition and retention suggests that a non-practice period that follows an effectively executed skill acquisition phase has no negative effect on performance of the acquired skills (Arthur et al. 1998; Ward et al. 2012; Kantak & Winstein 2012; Spampinato & Celnik 2021), and the present study unsurprisingly concurs with this notion.

Quantitative progress in handstand balancing time was statistically significant for all groups with no statistically significant differences between groups ($p = 0.609$), demonstrating that 2 training sessions a week can be effective in developing the skill of handstand, and that the skill-training break was not detrimental for skill acquisition. Qualitative progress in handstand form was statistically significant for both groups with the skill-training break ($p = 0.011$ and 0.001 respectively), but not for the handstand-only group ($p = 0.059$), suggesting that including periods focusing on prerequisite strength instead of the specific skill might be beneficial for the specific skill in the long term. As the starting level of the handstand-only group was coincidentally higher than the other two groups, smaller progress on handstand form could be due to diminishing returns, but since the coincidentally higher level of the handstand-only group disappeared during the intervention, it seems more likely that the differences in progress are due to either the absence of specific skill-training or the presence of strength training during those two weeks. Due to the relatively short duration of both the training break and the intervention itself, one should refrain from drawing strong conclusions yet. Nonetheless, the results are encouraging for everyone aiming to train and retain a wide variety of different motor skills.

The high drop-out rate must be noted when interpreting the results of the present study, since of the 511 participants who started, only 41 completed the study. While the technical difficulties and video-only interaction related to a fully online training and testing likely factor in the drop-out rate, the possibility of a selectivity bias exists. Having only high responders complete the study does not seem likely, but due to non-normally distributed results, the possibility cannot be dismissed out of hand. The ones who completed the study could also be among the most motivated of the group, and since motivation has been shown to be a factor in motor learning – both indirectly by ensuring adherence to training (Arthur et al. 1998, Ward et al. 2012) and directly by potentiating the learning-related neural adaptations (Spampinato & Celnik 2021) – it is possible that more motivated individuals both adhere and respond better to training. However, since motivation was not measured, its' effect on adherence or progress is mere speculation. Further research is both needed and warranted.

8.1 The effect of the skill-training break

The skill-training break did not have a statistically significant effect on improvement throughout the intervention, supporting the hypothesis. The handstand-only group (A) doubled their balancing time, going from 3.73 ± 7.38 to 7.35 ± 8.02 seconds ($p = 0.001$), while the combination of skill-training break groups (B+C) went from 1.11 ± 1.46 to 6.05 ± 7.92 seconds ($p = 0.001$), essentially improving 445 %. The qualitative assessment of handstand form went from 1.08 ± 1.12 to 1.46 ± 0.52 ($p = 0.059$) for the handstand-only group and from 0.68 ± 0.88 to 1.61 ± 0.63 ($p = 0.001$) for the combination of skill training-break groups. Improvement in handstand form was statistically significant for both skill training-break groups B and C ($p = 0.011$ and 0.001, respectively), but didn't reach statistical significance for the handstand-only group ($p = 0.059$), suggesting that the 2-week strength training phase was more beneficial for handstand form than specific handstand training.

The possibly diminishing returns related to higher starting level of group A might partially explain the smaller progress of the handstand-only group, but since the other groups essentially caught up to the level – or surpassed it – the likelihood of the between-group differences being due to the training intervention itself seems higher, suggesting that at some points prioritizing prerequisite strength is more beneficial than the specific skill work. The observed neutral or beneficial effect of the strength training phase could arise from addressing the prerequisite physical attributes that have been shown to correlate with handstand performance (Hedbávný et al. 2013b), thus potentially functioning as a foundation-laying accumulation phase as described by Stone et al. in their review on block periodization for sports performance (2021).

Kantak & Winstein (2012), Ward et al. (2012) and Healy et al. (2014) described how the introduction of desirable difficulties – such as random-order training or contextual interference – within the learning process can lead to greater between-session improvement and skill retention despite being worse for within-session performance. While a 2-week break from skill-training is not the same as random-order training or contextual interference introduced within single training sessions, it is possible that the skill-training break and some of the associated difficulties – such as having to initiate the learning process again – are beneficial for learning. The review by Spampinato et al. (2021) described how error-based learning and reinforcement learning are both better than use-dependent, repetition-based learning. It seems possible that a 2-week break from specific skill work could help prioritize elements from error-based learning and reinforcement learning over use-dependent learning by avoiding getting into excessively monotonous and repetitive mindset. This could – however – be avoided merely by designing skill training in a way that emphasizes the role of sensory prediction errors of error-based learning and reward-prediction errors of reinforcement learning by offering novel tasks or variable environmental constraints around the desired motor skill.

Neural adaptations to strength training – while include an element of skill acquisition – are distinct from those related to motor skill learning (Gabriel et al. 2006, Folland & Williams 2007). Since strength training is thought to increase neural drive via alterations in cortical and subcortical structures such as inhibitory cortical interneurons and reticular formation (Skarabot et al. 2021) instead of the reorganization of sensorimotor maps of the primary motor cortex associated with motor learning (Spampinato & Celnik 2021), it seems unlikely that the 2-week strength training phase elicited handstand-specific reorganization of the primary motor cortex. The spinal level alterations related to motor learning have been shown to be highly task-specific (Adkins et al. 2006, Wolpaw 2007), further supporting the notion that the training adaptations of the strength training phase are distinct from those related to skill learning, thus suggesting the lack of between-group differences are due to residual effects or permanence of skill-training adaptations elicited by the skill acquisition period. However, due to lack of neural measurements the specific sites of adaptation cannot be determined and the possibility of strength training eliciting some handstand-specific neural adaptations – while seemingly unlikely – cannot dismissed out of hand.

8.2 The effect of the timing of skill-training break

The timing of the training break affected only one measurement point: comparison of the skill-training break groups B and C showed significant differences associated with the timing of the training break in favour of the group who had the break later (p = 0.001 for quantitative and p = 0.004 for qualitative measurements) at 2nd mid-test, but not at any other tests. This is fully in line with the hypothesis: the difference between 5 and 7 weeks of training is meaningful, but the other measurement points show no difference. The finding that all between-group differences disappeared by later measurements suggests that in a short-term setting training should be more specific to the goals, but in longer term it is just as – if not more – beneficial to include less specific, foundation-laying training periods without worrying about the specific skill.

Comparison of the handstand-only group (A) and the late skill-training break group (C) showed a statistically significant difference on handstand balancing measurement (p = 0.030) at the same testing point – the 2nd mid-test – but not in any other measurements. Interestingly, groups A and C trained similarly up to the 2nd mid-test that showed the only difference between the groups. The finding that group C not only caught up to, but surpassed group A by 2nd mid-test, as well as the notion that no other measurement point showed meaningful between-group differences suggests that the potentially diminishing returns related to higher initial handstand skill level of group A might not be a meaningful factor. The higher initial strength level of group C – 18 ± 12 push-ups against 14 ± 11 of group A – did not reach statistical significance (p = 0.519), yet moderate correlation was shown between initial strength level and hand-balancing progress of group C (r = 0.664, p = 0.006), but not group A (r = 0.433, p = 0.068), making the initial strength levels an unlikely, but not completely impossible factor.

Reviews on skill retention have highlighted initial aptitude and individual ability as being among the most influential factors in skill retention (Arthur et al. 1998, Ward et al. 2012), and for a group of this level, i.e., beginners, the difference between 5 and 7 weeks of training can be a significant factor in developing the level of aptitude that negates the detrimental effect of the training break. In terms of block periodization, the timing effect of the training break could suggest that the residual effect of a 7-week long skill-training phase carries over a 2-week break from specific training better than a 5-week long phase, suggesting that the foundation-laying accumulation phase should be longer for individuals just getting started with the specific skill in question. However, the finding that all between-group differences disappeared by later measurements highlights how looking at short-term progress can be misleading. This mirrors the notion that certain practices that lead to seemingly slower learning within the training session can lead to worse long-term progress and retention (Ward et al. 2012; Healy et al. 2014), but in a wider time-course. However, as far as adherence to training and motivation are concerned, implementing longer accumulation phases for novel skills might be advisable.

8.3 Non-linearity of motor learning

While the improvements in all groups were statistically significant between pre- and post-tests, the improvement throughout the intervention was not linear for any of the groups. The results were in line with the hypothesis – motor skill learning is not linear (Dayan & Cohen 2011; Schöllhorn et al. 2012), and certain practices leading to seemingly worse short-term progress can lead to better retention (Ward et al. 2012; Healy et al. 2014). The results are not surprising, since in addition to having a 2-week period of non-specific training for two of the groups, the skill training intervention of the present study was designed to prioritize variable practice, contextual interference, and the use of external focus – elements that are known to lead to better transfer and retention at the expense of short-term performance.

As a balancing skill, handstand relies heavily on the integrated function of the nervous, vestibular, and proprioceptive systems (Gautier et al. 2007; Hedbávný et al. 2013a; Olchowik et al. 2015; Omorczyk et al. 2018). Mirroring this against the review on neurophysiology of motor learning by Spampinato & Celnik (2021) suggests that the skill of hand balancing could benefit greatly from practices prioritizing the combination of the cerebellum-related process of error-based learning and the basal ganglia-related process of reinforcement learning. Reinforcement learning has been shown to be initially slower, but to lead to longer retention (Therrien et al. 2016), which is why the present study incorporated elements of it in the training intervention. Due to the importance of appropriate collection and interpretation of vestibular, sensory, and proprioceptive information in balancing a handstand, the training intervention prioritized error-based and reinforcement learning over use-dependent learning, though it must be stated that learning by action observation might be mediated via the same neural processes underlying use-dependent learning (Spampinato & Celnik 2021), making it a potentially important mechanism in any video-based training intervention.

Periodization deals in creation and management of longer timelines (Farrow & Robertson 2017, Stone et al. 2021), and the non-linear nature of motor learning should be accounted for when designing training plans or testing intervals. The logical cycle of accumulation phase, followed by transmutation phase, leading to realization phase has been shown to be effective for the development of many physical performance traits (Stone et al. 2021), and the present study concurs with Farrow & Robertson (2017) in supposing that a similar logic of periodization can be applied to motor skill learning. One key implication of the results related to timing of the break is the importance of appropriate testing intervals: seeing the results of a successful accumulation phase might require the subsequent transmutation and realization phases and thus judging the effectiveness of a training program by a test at the middle of an accumulation phase might be misleading. Comparison of groups B and C demonstrate this beautifully, since the significant difference seen at 2nd mid-test represents testing the specific performance level the during an ongoing accumulation phase versus at the end of it.

8.4 The role of initial general strength level

The moderate, statistically significant correlation between initial pushing strength and improvement in handstand balancing time ($r = 0.537$, $p = 0.021$) was unsurprising, as was the finding that the correlation between strength and progress was greatest ($r = 0.664$, $p = 0.006$) for the group with – coincidentally – higher push-up repetition maximum. Hedbávný et al. (2013b) found the correlation between push-up strength and handstand balancing time to be strong ($r = 0.718$, $p < 0.0003$), and the results of the present study line up with their findings. In contrast, the lack of correlation between initial pushing strength and improvements in qualitative handstand form ($r = -0.002$, $p = 0.503$) is surprising, especially since Hedbávný et al. (2013b) found a moderate correlation between push-up strength and handstand form quality ($r = -0.687$, $p = 0.0006$). The negative correlation of the Hedbávný et al. (2013b) study is due to form being assessed as deductions, with 0 being flawless. In mirroring the findings of the present study against the Hedbávný et al. study (2013b), it must be noted, that they measured performance, whereas the present study measured progress.

Interestingly, while the present study found no statistically significant correlation between initial strength and improvement in handstand form, the groups with the skill-training break – i.e., strength training phase – showed greater improvements in handstand form than the handstand-only group, who was the only one to not gain statistically significant improvements in form quality. The well-established notion that handstand practice requires – and benefits from – upper extremity strength (Hedbávný et al. 2013b; Kochanowicz et al. 2019; Mizurori et al. 2021) likely still holds true, but with some caveats. Studies on hand-balancing in more difficult settings – such as the Kochanowicz et al. paper examining handstands on different gymnastic apparatuses (2019) and the Mizutori et al. paper on pike press to handstand (2021) – highlight how strength can be key in unlocking more advanced handstand-possibilities, and the findings of the present study merely suggest the classically desired, gymnastic-type handstand form might not be among the more advanced skills of high strength requirements.

Push-up repetition maximum for the combination of skill-training break groups B+C increased to a statistically significant degree ($p = 0.05$), suggesting that 2 training sessions a week for two weeks can be adequate to improve pushing strength. The average of all groups showed statistically significant improvement in strength (14 ± 36 %, $p = 0.001$), but a group-by-group examination showed that the improvements in handstand-only group A and the early skill-training break group B did not reach statistical significance ($p = 0.058$ and $p = 0.206$, respectively), indicating that they successfully maintained their initial strength levels, while the late skill-training group C improved (18 ± 29 %, $p = 0.007$). The greater, statistically significant improvement of the late skill-training brake group C compared to not statistically significant progress of the early skill-training brake group B indicates that the residual effect from such a 2-week strength training phase carries over 3, but not 5 weeks. Seeing as a review by Sousa et al. found training-induced strength gains to be reversed after 2–4 weeks (2019), this, too, seems to line up with previous evidence.

Overall, the present study lines up with existing literature in stating that a comprehensive handstand practice and high-level performance requires upper extremity strength, thus suggesting that inclusion of training phases prioritizing the prerequisite strength would be advisable in the long-term. The subjects in Hedbávný et al. study (2013b) were stronger than the those of the present study – with a push-up repetition maximum of 36 ± 7, versus the 14 ± 12 in the present study – and since the present study found the correlation between balancing progress and strength to be greater for the stronger group, it would be interesting to test how far the trend of higher strength level benefiting hand-balancing to a greater degree extends.

8.5 Strengths and limitations of the study

The greatest strength of the present study was the experimental design which examined the effect of a skill-training break while accounting for the relative permanence of skills and the well-known reversibility of strength. The skill-training break included the same amount of training sessions, but their content was different, thus addressing the question of specific skill-training, and not physical activity in general. Among the other strengths of the present study is that the entire training intervention as well as all testing was completed as an online course, which both allowed for recruitment of a large number of participants and made the training intervention possible even during the covid-related restrictions that prevented most of the ongoing research at the time.

While the online course-nature of the study was among its’ greatest strengths, it can also be seen as a key weakness, since instructing the training sessions and/or performing the measurements in person might have allowed for greater interaction with the participants, leading to both greater adherence to the training plan and more accurate measurements. The online course also required researchers to rely on self-reported statements regarding adherence to training. Due to technical difficulties, there were challenges in dealing with the number of videos and online-communication. Part of this was unavoidable, yet there is clear room for improvement in the informational logistics of doing a training intervention study for 500 people.

The duration of both the training intervention itself and the skill-training break was long enough to address some questions around periodizing skill training, yet the non-training period was nowhere near long enough to address the question of skill permanence and retention. The length of both the intervention and the skill-training break was chosen to mitigate motivational problems and drop-outs. Determining whether acquired motor skills can be permanent in a similar way as stable memories have been shown to be would require a non-training period that lasts for months or years, while maintaining the physical prerequisites.

The lack of neural measurements is among the greatest limitations of the present study, though due to COVID-19 and the restrictions of early 2021 laboratory measurements were not an option in this study. The training intervention was designed to account for different neural adaptations for skill vs. strength training as well as the reversibility of neural and morphological adaptations related to strength training, but without laboratory measurements we can but speculate whether the adaptations occurred as expected. The intervention was able to successfully show performance changes related to periodization decisions, thus confirming each hypothesis, but further research is needed to determine the specific sites of adaptation behind observed performance changes.

8.6 Conclusions

The foundation of periodization is built upon the understanding of training adaptations, residual effects, decay rates and non-compatible fitness factors (Stone et al. 2021), and while the present study did not study the mechanisms behind skill acquisition, it demonstrated how a logically periodized and appropriately programmed skill acquisition program elicited performance changes that behave exactly as expected based on existing information of the underlying training adaptations. The methodological attempt to manage training adaptations – that has been shown to produce greater performance adaptations on strength and power compared to non-periodized methods (Stone et al. 2021) – seems to be justified in skill acquisition.

Neural adaptations between maximal strength training and motor skill learning have been shown to be markedly different; motor skill training involves reorganization of sensorimotor maps in the primary motor cortex, whereas strength training involves alterations in cortical and subcortical inhibitory interneurons and the reticular formation (Skarabot et al. 2021). While physically challenging motor skills – such as handstands – include elements both of strength and skill, trying to train them both with the same training modality is sub-optimal. Both should be trained – but separately – preferably following a logically designed periodization plan that accounts for the differential adaptations.

8.7 Practical applications

The general logic behind periodization goes from general to specific in a cyclical manner, alternating between widening the foundation and sharpening the peak. The ability to incorporate periods that completely neglect the specific skill elements without losing said skill elements has noteworthy implications for training load and fatigue management, especially for practitioners aiming to train several different disciplines. The primary premise of block periodization as the sequencing of training phases – accumulation, transmutation, and realization phase – in a logical order, as supported by evidence (Stone et al. 2021), seems to be applicable to skill acquisition. Findings of the present study suggest that provided the accumulation phase of foundational skills incorporates variable practice and contextual interference, the residual effects of the phase persist for at least two weeks without any specific training.

Key aspect of designing successful training cycles is recognizing which elements or fitness factors serve as a foundation for the desired, specific skills. In the training intervention and periodization plan of the present study, the skill of balancing was considered a more specific element that is built upon the foundation of body awareness and shoulder stability. Therefore, the elements prioritized during the accumulation phase included understanding of safe handstand practice, awareness of body position, and shoulder stability. An appropriate combination of declarative and procedural information of the task – i.e. a combination of cognitive understanding and the performance of the skill itself – has also been shown to ensure strong durability and generalizability of the learnt material (Healy et al. 2014), suggesting that an appropriate accumulation phase of a periodized motor skill training program should include both the training of foundational elements of the desired skills and explanations of why the elements are important.

The transmutation phase started to incorporate more balancing, but in a way that relied heavily on the use of external focus and variable tasks while still focusing on shoulder stability and body awareness. The realization phase focused more on specific handstand balancing tasks. The 2-week strength training phase can either be seen either as a break from specific skill-training, or an extension of the accumulation phase, focusing on the prerequisite strength. Given that the groups with the strength phase progressed more in qualitative handstand form, the strength training phase seemed to either address the physical requirements better than the specific training alone or potentiate the subsequent transmutation phase.

Correlation between strength and progress in handstand balancing ability suggests that an adequately task-specific, yet general strength should be considered a foundational element upon which more advanced movement options can be built. It’s important to note, however, how neural adaptations behind strength and skill are markedly different, implying that while both should be trained, they should be trained separately. Higher strength levels can, theoretically, decrease the relative intensity of skill training, therefore increasing the number of safe trials a practitioner can do in a skill-training session as well as improving the likelihood of adaptations involving the desired reorganization of sensorimotor maps of the primary motor cortex, instead of the more sub-cortical adaptations of maximal strength training. The goal of strength training for physically demanding skills should be to build a foundation that makes the specific skill-training lighter with respect to maximal strength levels, thus allowing for safer variable practice, greater freedom, and higher skill-training volume.

If the goal is to progress, adherence to training is crucial in the long run, highlighting the importance of motivation. Individuals likely look to gain different things from their physical training, therefore experiencing the non-linear nature of learning or breaks in specific training differently – some may enjoy detaching from training their main goal, while others may find it close to intolerable. This paper will not tell anyone how to organize their training or live their life but will hopefully offer some insight that helps make more informed decisions. Understanding the counter-intuitive and non-linear nature of learning, the subjectivity of the definition of success, and the expected time-course of different training adaptations can be helpful in finding some amount of patience, clarity, or peace of mind regarding physical training. Findings of the present study may hopefully alleviate the fear of losing specific skills due to detraining and encourage more variable, explorative practice.

Despite the clear limitations of the present study, the results encourage coaches and practitioners to trust the process of a logically designed periodization plan and to look at the long-term improvements. Block periodization together with numerous programming schemes offers a logical framework that allows for individualization, autoregulation, and a substantial amount of flexibility to account for the complexity of reality. While the short duration of the present study along with the lack of laboratory measurements prevent drawing strong conclusions, the results are promising. Further research – especially regarding adaptation mechanisms – is warranted.

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