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BY
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AALBORG UNIVERSITY
DENMARK

ON EFFECTS OF HEAVY STRENGTH TRAINING ON HUMAN VOLUNTARY RHYTHMIC MOVEMENT

PH.D. THESIS

BY

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AALBORG UNIVERSITY
DENMARK

A DISSERATATION SUBMITTED TO

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3. **Sardroodian, M**., Madeleine, P., Voigt, M., & Hansen, E. (2014). Frequency and pattern of voluntary pedalling is influenced after one week of heavy strength training. *Human Movement Science, 36,* 58-69.

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above.

ENGLISH SUMMARY

Despite distinct biomechanical differences between different kinds of rhythmic movements, these are suggested to be generated by similar types of neural networks. Freely chosen cadence (FCC) during submaximal cycling has been suggested to be under primary influence of central pattern generators. Thus, FCC may be a good reflection of central pattern generator movement rhythm output. It has been reported in several studies that heavy leg strength training involving both hip flexion and extension exercise caused recreationally active individuals to reduce their FCC during submaximal pedalling. The changed rhythmic movement behaviour was observed after 4 weeks of training where it was first measured. But, perhaps the change occurs even earlier, in response to neural adaptations. Furthermore, based on the common core hypothesis, it was proposed to observe the same effect of strength training on the motor control of different rhythmic movements. Still, knowledge on the primary neural adaptation following separate heavy extension and flexion strength training during different rhythmic movements is lacking. Therefore, the overall aim of this thesis was to provide new insights into the rhythmic movement behaviour by investigating the alteration in movement frequency and pattern during rhythmic movements after heavy strength training. For this purpose, three studies were performed.

In study (I), heavy hip extension strength training decreased the FCC after one week of training. Furthermore, minimum tangential pedal force (F_{min}) and crank angle at F_{min}, representing the rhythmic movement pattern, was altered after hip extension training. In study (II), there was a significant correlation between stride characteristics during walking and running. Besides, in contrast to results from study (I), no effects of heavy strength training were found on the stride characteristics during walking and running. In study (III), finger tapping characteristics were not influenced by heavy finger extension and flexion. Besides, freely chosen tapping frequency increased around 11% across the study period which contrasts the previous results from study (I).

The present findings suggested that the task specifications or characteristics of different neural networks controlling various rhythmic movements may explain the different observations in the present project.

DANSK RESUME

På trods af tydelige biomekaniske forskelle mellem forskellige typer af rytmiske bevægelser, er det blevet foreslået at det er lignende neurale netværk som genererer disse bevægelser. Selvvalgt kadence (SK) ved submaksimal cykling er blevet foreslået at være under indflydelse af såkaldte central mønstergeneratorer. SK kan derfor vise sig at være en god indikator for det rytmiske output fra de centrale mønstergeneratorer. Flere studier har rapporteret at tung styrketræning der involverer både hofte fleksion og ekstension har resulteret i en reducering af SK hos motionister under submaksimal cykling. Ændringen i den rytmiske bevægelse blev observeret efter 4 ugers træning hvor den blev målt første gang. Men ændringen kan potentielt være sket endnu tidligere pga. neurale adaptationer. Baseret på en common core hypotese, er det foreslået at effekten af styrketræning vil kunne ses på den motoriske kontrol af forskellige rytmiske bevægelser. Dog mangler der stadig viden om den primære neurale adaptation som sker efter tung fleksions- og ekstensions-styrketræning. Derfor var det overordnede mål for dette projekt at tilvejebringe ny indsigt i de neuromuskulære adaptationer ved at undersøge ændringen i bevægelses-frekvens og -mønster ved rytmiske bevægelser efter tung styrketræning. Til dette formål blev der udført tre studier.

I studie (I), nedsatte tung hofteekstensionsstyrketræning SK, efter en uges træning. Desuden ændrede hofteekstensionstræningen minimum tangentiel pedal kraften (F_{min}), og vinklen af kranken ved F_{min}, som repræsenterer det rytmiske bevægelsesmønster. I studie (II), var der en signifikant korrelation mellem skridtkarakteristika for gang og løb. Endvidere blev der ikke fundet nogen effekt af styrketræning på skridtkarakteristika under gang og løb, hvilket er i modstrid med resultaterne fra studie (I). I studie (III), blev karakteristika ved fingertapning ikke påvirket af tung træning af finger fleksion og ekstension. Endvidere blev den selvvalgt fingertapningsfrekvens øget med 11 % under studie sperioden, hvilket er i modstrid med de tidligere resultater fra studie (I).

De nuværende resultater indikerer at opgavespecificiteten eller egenskaberne af forskellige neurale netværk der kontrollerer forskellige rytmiske bevægelser kan være årsagen til de forskelligartede observationer i det nærværende projekt.

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This thesis would not have been possible without the support and encouragement of some people that I would like to mention here.

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I would also like to thank Professor *Michael Voigt*, for priceless inputs to the study (I) and (II) and all my colleagues for providing friendly, inspiring and competitive research environment. I also appreciate the participants who volunteered in the experiments of the current PhD study.

Finally, I would like to acknowledge the love and support I have received from my family. Particularly, I express my deep appreciation to my husband, Alireza, who supported and encouraged me during my PhD study.

Mahta Sardroodian
Aalborg, 2015

PREFACE

The present studies were carried out at Center for Sensory-Motor Interaction (SMI), Aalborg University, Denmark, in the period from 2012 to 2015.

This thesis is based on the following three articles. In the text these are referred to as Study (I), Study (II), and Study (III) (full-length articles in Appendix). Of note is that study (I) constitutes one out of nine articles, which forms the basis of a manuscript submitted by EA Hansen for acquiring a D.Sc. degree.

Study (I): Sardroodian M, Madeleine P, Voigt M, Hansen EA. **Frequency and pattern of voluntary pedalling is influenced after one week of heavy strength training.** *Human Movement Science*. 2014, 36, 58-69.

Study (II): Sardroodian M, Madeleine P, Voigt M, Hansen EA. **Freely chosen stride frequencies during walking and running are not correlated with freely chosen pedalling frequency and are insensitive to strength training**. G*ait & Posture. In revision.*

Study (III): Sardroodian M, Madeleine P, Mora-Jensen MH, Hansen EA. **Characteristics of finger tapping are not affected by heavy strength training.** *Journal of Motor behaviour. Submitted.*

Contents

LIST OF ABBREVIATIONS

ANOVA	: Analysis of variance
CI_{95}	: 95% Confidence interval
CON	: Control group
CPG	: Central pattern generator
CV	: Coefficient of variation
F_{max}	: Maximum tangential pedal force
F_{min}	: Minimum tangential pedal force
FCC	: Freely chosen cadence
HET	: Hip extension training group
HFT	: Hip flexion training group
ICC	: Intraclass correlation coefficient
LSD	: Least significant difference
1RM	: One repetition maximum
Ph_{neg}	: Phase with negative tangential pedal force
RFD	: Rate of force development
Rpm	: Revolutions per minute
SD	: Standard deviation

1 INTRODUCTION

This section presents a brief background and scope of the present project. The overall aim and the flow of the thesis are also presented.

1.1 NEUROMUSCULAR CONTROL DURING RHYTHMIC MOVEMENT

Activities such as walking, running, cycling and finger tapping represent rhythmic movements. They have been used as exercise model for human rhythmic movement studies (Balter & Zehr, 2007; Dietz et al. 1994; Hansen et al. 2015; MacLellan et al. 2012; Shima et al. 2011; Sternad et al. 2000; Teo et al. 2013; Zehr & Duysens, 2004; Zentgraf et al. 2009). Adequate control of voluntary rhythmic movement is of major importance for human quality of life, including those who recover from injury or disease and those who live in a healthy active life (Cambach et al. 1997).

Rhythmic movements in vertebrate species are generated by neural networks in the brain and the spinal cord. The spinal components are termed central pattern generators (CPGs), which are capable of producing pattern of rhythmic movement and, thus, are involved in the control of voluntary rhythmic flexion-extension exercise (Calancie et al. 1994; Dimitrijevic et al. 1998; Duysens & Van de Crommert, 1998; Zehr, 2005). It is generally acknowledged that both descending supraspinal drive and somatosensory feedback contribute in fine-tuning the output of human CPGs (Van de Crommert et al. 1998; Zehr & Duysens, 2004) (Figure 1 and 2). The morphology and function of CPGs in animals have been studied intensively (Grillner & Zangger, 1979; Perret & Cabelguen, 1980; Fedirchuk et al. 1998; Kiehn, 2006; McCrea & Rybak, 2008). However, studies on humans are not progressing as fast as studies on animals. A reason is that direct measurement of CPG output obviously is not simple to perform in humans, like in anesthetized or killed animals. Therefore, we have to rely on indirect and non-invasive investigations. Furthermore, it should be emphasised for completeness that the existence of human CPGs is difficult to conclusively prove (Calancie et al. 1994) as well as in other primates (Fedirchuk et al. 1998). However, indirect evidence has been reported in patients with spinal cord injuries (Calancie et al. 1994; Dimitrijevic et al. 1998) and in infants (Yang et al. 1998) to indicate the existence of functional CPG-like spinal neural networks. Further, for more understanding of nervous system organization and function, the analysis of motor behaviour can be used (Goulding, 2009).

The internal structure of CPGs is supposed to be divided into two components, one being a rhythm generator responsible for setting the rhythmic movement frequency and the other being a pattern generator responsible for generating the rhythmic movement pattern (Dominici et al. 2011; Kriellaars et al. 1994; McCrea & Rybak, 2008; Perret & Cabelguen, 1980) (Figure 2). Cycling has been used as an exercise model to study the freely chosen pedalling rate (Hansen et al. 2014). The latter reflects an innate voluntary rhythmic leg movement frequency that might also be linked to CPGs (Hansen & Ohnstad, 2008; Hartley & Cheung, 2013; Zehr, 2005). In the present project, freely chosen frequency during cycling, walking, running, and finger tapping has been considered to reflect the rhythmic movement frequency and tangential pedal force profile during cycling, stride phase characteristics during walking and running, and kinetic and kinematic characteristics during finger tapping have been considered to reflect the rhythmic movement pattern. This approach was inspired by a previous study of pedalling (Hansen et al. 2014).

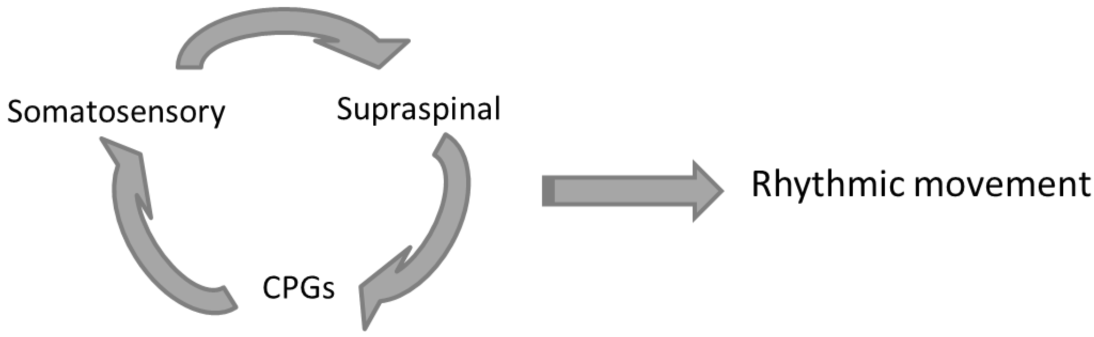

Figure 1*: Illustration of the tripartite system for regulation the human rhythmic movement. Modified from Zehr (2005).*

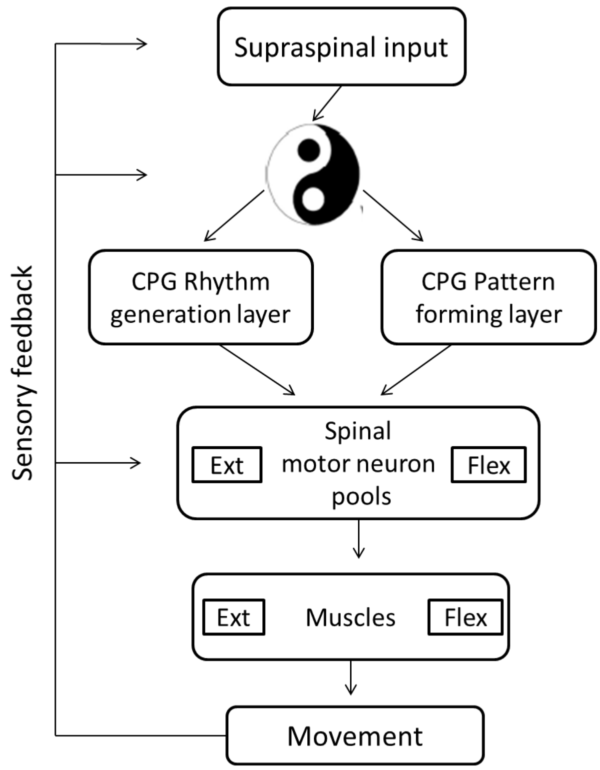

Figure 2*: Model representing role for supraspinal input, CPG (includes rhythm and pattern generation layers), and sensory feedback in the generation of rhythmic movement.*

1.2 COMMON CONTROL FOR RHYTHMIC MOVEMENTS

It has been proposed that the basic pattern of different rhythmic movements is generated by the activity of collections of neurons that are located at different levels of the central nervous system and termed CPGs (Van de Crommert et al. 1998; Zehr, 2005). As such, it has been assumed that there is at least one CPG for each limb and these CPGs are located in the spinal cord (Balter & Zehr, 2007; Duysens & Van de Crommert, 1998; Juvin et al. 2005). Furthermore, same central pattern generator mechanisms suggested that may regulate different patterns of movement in human (Zehr et al. 2007) (Figure 3). In support of this hypothesis, it has been reported that despite dissimilarity in kinematics (Li et al. 1999) and kinetics (Nilsson & Thorstensson, 1989) during walking and running, timing of muscle activation in running was accounted by five basic temporal activation components that had previously been found for walking (Cappellini et al. 2006). It caused the researchers of the latter study to suggest that even with distinct biomechanical differences between walking and running; these two types of locomotion are likely to be controlled by shared pattern-generating networks. In addition, similarity of muscle synergies during walking and cycling has been reported that may sequentially indicate similar synergies and modular control through different rhythmic movements (Barroso et al. 2013). Therefore, it could be speculated that different rhythmic movements may be influenced in a same way against an exposure such as heavy strength training, supporting the notion that they may share similar neural networks.

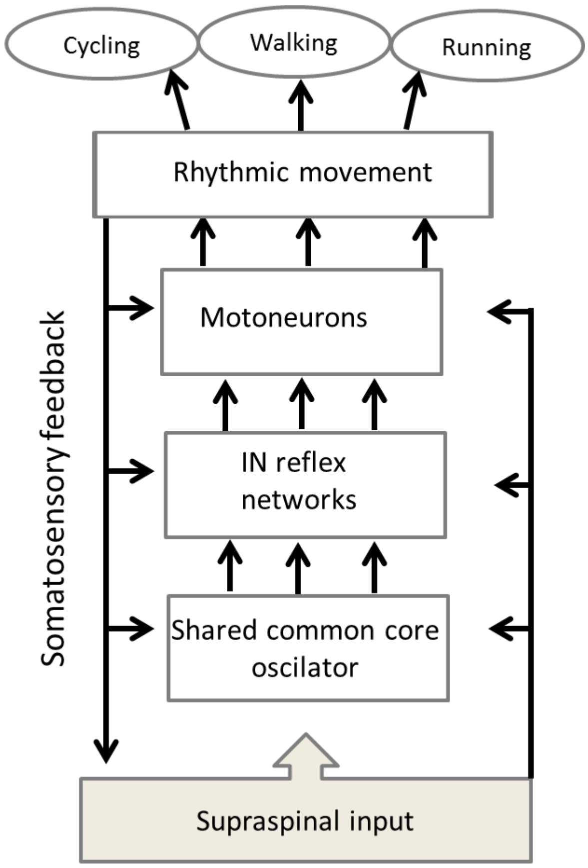

Figure 3: Model representing that rhythmic movement is generated by coordination of CPGs, supraspinal input, and somatosensory feedback. Modified from (Zehr, 2005).

1.3 HEAVY STRENGTH TRAINING

Strength training is a common part of many sports aiming at development of strength and performance (Delecluse, 1997; Wisløff et al. 2004). Furthermore, it has been reported that strength training alters the human voluntary rhythmic leg movement behaviour by decreasing the freely chosen pedalling frequency in recreationally active individuals (Hansen et al. 2007; Rønnestad et al. 2012). Although such a reduction is not reported for well-trained cyclists (Rønnestad et al. 2012). Various effects of strength training on both descending and afferent inputs to the spinal neural networks have been speculated to be involved in the reduction of pedalling frequency (Hansen et al. 2007; Rønnestad et al. 2012). In the following these effects will briefly be presented. Strength training may down-regulate group Ib sensory nerve feedback from the force-sensitive Golgi tendon organs at a given constant level of loading (Aagaard et al. 2000). Such a down-regulation may result in less excitatory input to the CPGs being responsible for the rhythmic movement (McCrea, 1998; Lam & Pearson, 2001; Windhorst, 2007) thereby causing participant to decrease the freely chosen cadence (FCC) towards a lower and more force requiring pedalling frequency. Another possibility is that after strength training, motor units produce more force than prior to the training (Carroll et al. 2011) thus, fewer motoneurones are required to be recruited during muscle contraction (Carroll et al. 2011; Carroll et al. 2002). This reduction in required recruitment would be reflected in decreased cortical activation which was interpreted for enhanced neural efficiency (Falvo et al. 2010). In turn, strength training may reduce the common descending supraspinal drive (De Luca & Erim, 1994) to the CPGs (Minassian et al. 2007). Such a reduction may reduce the net excitation of CPG that cause to reduce the movement frequency output of CPG.

Heavy strength training for 12 weeks including both hip flexion and hip extension exercise has been reported to decrease the FCC by an average of 8 to 11 rpm during submaximal cycling in recreationally active individuals (Hansen et al. 2007). Interestingly, reduced FCC was observed after four weeks of strength training that was the first measuring of cadence (Rønnestad et al. 2012). However, it is possible that the FCC is reduced even earlier than four weeks. Actually, if the reduction of cadence is a result of neural adaptations, it could be hypothesised that this reduction to occur already in the very initial phase (first couple of weeks) of the strength training period (Gabriel et al. 2006). Furthermore, it is unclear whether one of the training forms (hip extension or flexion exercise) had a particular effect on the reduction of FCC. Therefore, understanding of the rhythmic movement behaviour could be enhanced by exploring the temporal effects of separate heavy extension and flexion strength training on the voluntary rhythmic movement frequency and pattern. Besides, it could be speculated that the freely chosen frequency in different rhythmic movements, such as walking, running, and finger tapping would be affected by heavy strength training in a same way as cycling has previously been shown to be (Hansen et al. 2007; Rønnestad et al. 2012).

1.4 AIMS OF THE PHD PROJECT

The overall aim of this thesis was to provide new insights into the movement behaviour during various voluntary rhythmic movements. For this purpose, the effects of strength training on frequency and pattern of four different rhythmic movements was studied. The flow of the thesis is illustrated in Figure 4.

The specific aims of this Ph.D. project were:

1. To investigate the effects of 4 weeks hip extension and hip flexion training on freely chosen frequency and pattern during submaximal cycling **(Study I)**

2. To investigate the correlation between freely chosen frequencies during walking, running, and cycling and investigate the effects of 4 weeks hip extension and hip flexion training on freely chosen frequency and pattern during walking and running **(Study II)**

3. To investigate the effects of 2 weeks index finger extension and flexion training on freely chosen frequency and pattern during index finger tapping **(Study III)**

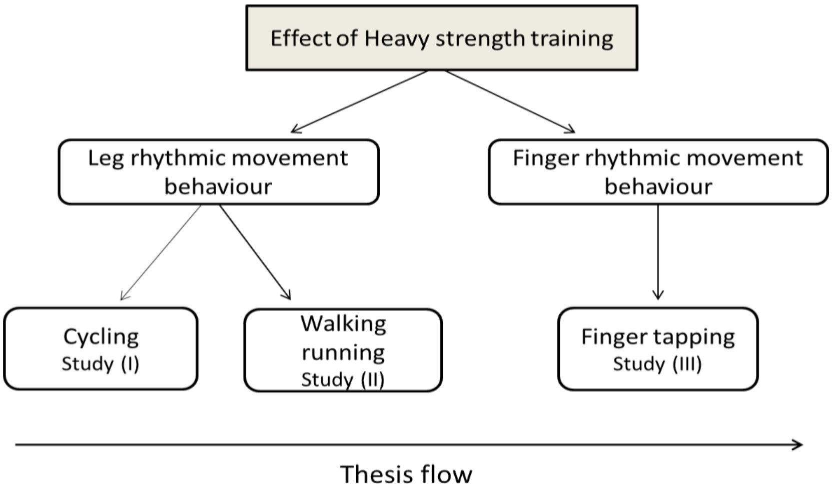

Figure 4*: overview of the performed studies.*

2 METHODS

The following section provides an overview of the methods used in the three studies.

2.1 PARTICIPANTS

A total of 51 healthy recreationally active participants took part in the three studies. The baseline anthropometrical measures, age and number of participants of each study are shown in Table 1. For study (I), all participants were well accustomed to cycling as bicycling was occasionally performed for personal transportation. For Study (III), none of the participants had any history of neural or muscular diseases, or other disorders related to the right hand, arm, or shoulder and none of them had used their right index finger to a large extent. None of the participants in all the studies had performed any strength training during the preceding six months and they maintained normal daily activity during the course of the studies. All the studies were conducted according to the declaration of Helsinki and approved by the local ethical committees (Approval no. N-20110025). Informed consents were obtained from all participants.

Table 1: Characteristics of the participants in study (I -III).

	Study	
	(I) & (II)	**(III)**
Participants	27 (14 men, 13 women)	24 (11 men, 13 women)
Age (years)	24.1±5.0	23.5±2.9
Body mass (kg)	70.2±10.6	71.8±10.6
Height (m)	1.78±0.09	1.74±0.1

The population in the study (II) was the same as in study (I).

An overview of the methods used in the studies is summarized in Table 2 and described in more detail below.

Table 2: Overview of the interventions and measurements in study (I- III).

	Study		
	(I)	**(II)**	**(III)**
Hip flexion and extension strength training	X	X	
Finger flexion and extension strength training			X
Maximal strength	X	X	X
Rhythmic movement frequency	X	X	X
Rhythmic movement pattern	X	X	X

2.2 HEAVY STRENGTH TRAINING (STUDY I-III)

In studies (I) and (II), heavy hip extension and hip flexion exercises were performed by HET and HFT groups, respectively. Training sets were alternately made with right and left legs. Prior to exercise in order to warm-up, participants performed 10 minutes cycling on the cycle ergometer at a self-selected intensity that was followed by two to three warm-up sets with gradually increased load of the exercise. The total duration of the training period was 4 weeks. During the first three weeks of the strength training period, participant trained with 10RM sets (i.e., with a load that can be lifted 10 times in a set) at the first weekly session and 6RM sets at the second weekly session. During the last week of the training period, the loads were set to 8RM and 5RM in the sets for the first and second weekly sessions, respectively. Three sets of the relevant training exercise were performed during each training session (Rønnestad et al. 2010) (Table 3). The targeted muscles in the present hip extension and hip flexion exercises include the gluteus maximus muscles and the iliopsoas muscles, as these muscles contribute to propulsion and power in walking, running, and cycling (Sasaki & Neptune, 2006; So et al. 2005).

In study (III), heavy finger extension and finger flexion were performed for 2 weeks and 2 sessions per week. The participant always performed the extension exercise before the flexion exercise. First, 10 repetitions at 60% of 1RM was performed for one warm-up set. Then participant trained with 10RM- and 6RM-sets for the first and second weekly session, respectively. Furthermore, during each training session, three sets of the applied training exercise with one min rest in between were performed (Table 3). The target muscles in the present index finger extension and index finger flexion exercises include the extensor digitorum and flexor digitorum profundus, respectively (Keen & Fuglevand, 2004; Reilly et al. 2004).

All training sessions were supervised by an investigator of the study to ensure 100% compliance.

***Table 3**: Overview of the heavy strength training included in study (I-III).*

	Study	
	(I) and (II)	(III)
Sessions	8	4
Sessions per week	2	2
Sets per session	3	3
Repetitions per set	10, 8, 6 or 5	10 or 6
Load	10, 8, 6 or 5RM	10 or 6RM

2.3 DETERMINATION OF MAXIMAL STRENGTH (STUDY I-III)

The maximal load that could be lifted in one repetition (1RM) was determined as maximal strength. Strength tests were always preceded by 10 min warm up on the cycle ergometer (in studies I and II) or three sets of 10 repetitions at a load of 50% of the estimated 1RM (in study III). All studies followed the standardised protocol consisting of three sets with gradually increased loads (70%, 75% and, 80% of the estimated 1RM load) and decreased number of repetitions (10, 7 and 5) (Walker et al. 2009). The first 1RM attempt was then performed with a load approximately 5% below the predicted 1RM load. In study (I) and (II), after each successful attempt, the load was increased by 2-5% until the participant failed to lift the load for 2-3 consecutive attempts. In study (III), after each successful attempt, the load was increased by 0.2 kg until an attempt was failed. After a failed attempt, a final attempt at 0.1 kg less was completed. One min of rest separated all sets and single repetition attempts in all studies.

2.4 FREELY CHOSEN FREQUENCY DETECTION AND RECORDING (STUDY I-III)

All test sessions in three studies were performed at the beginning of each week and at the same time of the day for each participant. The former was to avoid circadian rhythm effects on the results (Moussay et al. 2002). In study (I), the participant performed 11 min of continuous cycling at 100 W, gear 8 on the SRM cycle ergometer (Schoberer Rad Messtechnik, Jülich, Germany). This setting ensures a constant power output regardless of the cycling cadence. Freely chosen cycling cadence was applied for the first six min The participant was asked to try to cycle in a desired and relaxed way without focusing particularly on the actual pedalling. Cycling cadence was blinded to the participant. The FCC was noted at the end of each minute of cycling and subsequently an average across the 1st to 6th min was calculated. During the 6th to 11th min, the participant was asked to cycle at a target cadence of 60 rpm.

In study (II), participants performed 5 min of walking at 4.0 km per h followed by 5 min of running at 8.4 km per h. Participants were instructed to walk and run in a relaxed and preferred way and e.g. imagine walking or running outside on a road. The freely chosen stride rate during walking and running was recorded using two pressure-sensitive sensors (SFR 174, I.E.E., Contern, Luxembourg) under each sole of the two feet. The four sensors were connected to custom-built amplifiers. During the last min of each walking and running the signals were sampled at 2000 Hz through a 16 bit A/D converter using a custom made LabVIEW-based software (LabVIEW, Austin, Texas, USA).

In study (III), the participant was instructed to sit in an office chair in front of a table comfortably. The back of the participant was kept straight. The right forearm was resting on the table and finger tapping was performed at a comfortable and preferred frequency for 3 min with the right index finger on a force transducer (AMTI, Watertown, MA, USA). The remaining four fingers of the right hand were kept straight and relaxed. The freely chosen finger tapping was recorded by using a 3D motion capture system (Standard VZ-4000v, Phoenix Technologies Inc., Burnaby, BC, Canada) during the last 90 s of the tapping bout. For kinematical recording by a 3D motion capture system, a LED-tracer was attached to the nail of the participant's index finger. The tapping frequency was calculated by dividing the total number of maxima value of tapping movement by 1.5 min.

2.5 MOVEMENT PATTERN DETECTION AND RECORDING (STUDY I-III)

In study (I), tangential pedal forces which reflected the rhythmic movement pattern were sampled using two Powerforce system force pedals (Radlabor GmbH, Freiburg, Germany) mounted on the cycle ergometer. The data was sampled at 2000 Hz using a 16 bit A/D converter during the last minute of each of the two cycling conditions. A data acquisition LabVIEW-based software, IMAGO Record (part of the Powerforce system), was used for sampling. The five selected key characteristics contained maximum tangential pedal force (F_{max}) and minimum tangential pedal force (F_{min}) measured in N, crank angles at F_{max} and at F_{min} measured in degrees, as well as phase with negative tangential pedal force (Ph_{neg}) measured in degrees.

In study (II), stride phase characteristics which reflected the rhythmic movement pattern consisted of the duration (s) of stance phase, swing phase and stride, as well as stride rate (strides per min) were recorded using two pressure-sensitive sensors under each sole of the two feet (see section 2-4). The LabVIEW- based software was computed and saved data for both feet during the last minute of each walking and running.

In study (III), kinetic and kinematic characteristics during finger tapping which reflected the rhythmic movement pattern were computed from each single finger tap and consisted of: Peak force (in N), time to peak force (in ms), duration of the finger contact phase (in ms), rate of force development (RFD, in N/s), and, fingertip displacement (in mm). Tapping force was measured in the sagittal plane and vertical direction on the force transducer (see section 2-4). The tapping force signal was amplified 4000 times, low-pass filtered at 1050 Hz and digitalised using a 12 bits NI BNC-2090A A/D-board (National Instruments, Austin, TX, USA). Sampling was performed at 2000 Hz during the last 90 s of the tapping bout. The recordings were executed using LabVIEW-based software (Mr. Kick III software, Aalborg University, Aalborg, Denmark). Furthermore, the finger movement was recorded using a 3D motion capture system and sampled at 200 Hz synchronously with the tapping force using VZSoftTM software (Phoenix Technologies Inc., Burnaby, BC, Canada) during the last 90 s of tapping bout.

2.6 DATA ANALYSIS

An overview of the reported variables are summarized in Table 4 and further described below.

Table 4*: Overview of the reported variables in study (I -III).*

	Study		
	(I)	(II)	(III)
1RM extension load (kg)	X	X	X
1RM flexion load (kg)	X	X	X
Freely chosen movement frequency (rpm)	X	X	X
F_{max} (N)	X		
F_{min}(N)	X		
Crank angles at F_{max} (˚)	X		
Crank angles at F_{min} (˚)	X		
Ph_{neg} (˚)	X		
Duration of stance phase (s)		X	
Duration of swing phase (s)		X	
Stride duration (s)		X	
Stride rate (strides min^{-1})		X	
Peak force (N)			X
Time to peak force (ms)			X
Duration of finger contact phase (ms)			X
RFD (N/s)			X
Fingertip displacement (mm)			X

2.6.1 MUSCLE FORCE PARAMETERS (STUDY I AND III)

In study (I), for analysing the tangential pedal forces, a trigger was used by power force system for generating a square wave pulse when the left crank arm passes a vertical position with the pedal in top position. This pulse was used to cut the data into distinct cycles of pedal force data. Subsequently, the IMAGO software calculated the average crank cycle tangential pedal force profiles for left and right pedal, respectively. Then, a single set of tangential pedal forces calculated as an average of data from both left and right pedal force (Figure 5).

In study (III), the following four force profile characteristics were analysed from each single finger tap from valid taps (determined by visual assessment for wrong taps, following automatic detection) during the last 15 s of recording period. (*i*) Peak force (in N), determined as the maximal impact force during the primary impact phase (Dennerlein et al. 1998; Jindrich et al. 2003; Lee et al. 2009). Peak force was calculated as the difference between the baseline value considered across a 40 ms period before force onset and the maximal value of the impact force. The force onset was determined from the differentiated force signal using threshold detection. (*ii*) Time to peak force (in ms), measured from the force onset to the peak force. (*iii*) Duration of the finger contact phase (in ms), measured from the force onset until the force returned to the baseline, representing the force offset. (*iv*) Rate of force development (RFD, in N/s), determined on the basis of first derivative of the peak force signal (df/dt) in LabVIEW. This was done using peak detection technique. The maximal RFD was detected as the maximal point between the force onset and the point which zero force rate was reached. Finally, the average values of four variables across the last 15 s of the tapping bout were calculated for each participant (Figure 6).

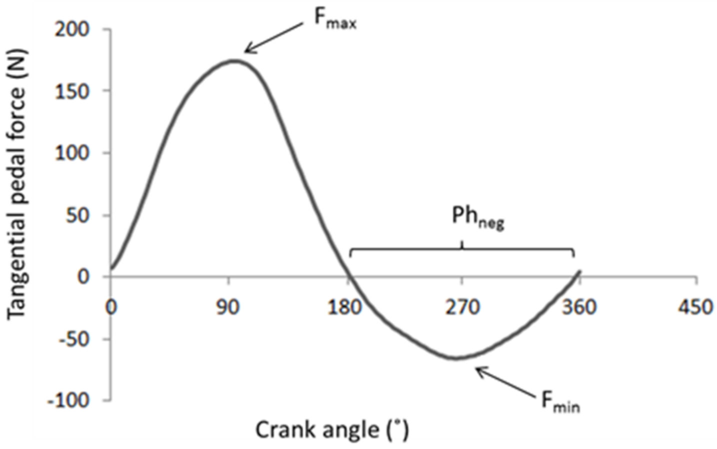

Figure 5*. A data example showing a tangential pedal force profile for the right pedal. Characteristics of the profile are illustrated. This figure is modified from study (I).*

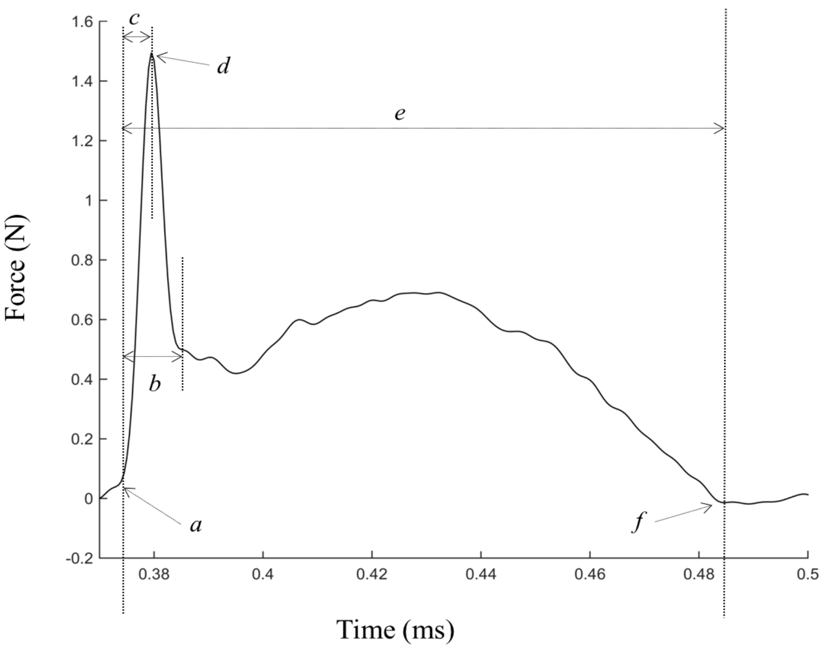

Figure 6*: Data example (n=1) during a single finger tap of recorded force. Superimposed on the force profile are indications of (a) force onset, (b) impact phase, (c) time to peak force, (d) peak force, (e) duration of the finger contact phase, and (f) force offset. Modified from study (III).*

2.6.2 STRIDE PHASE CHARACTERISTICS (STUDY II)

In study (II), for analysing the stride phase characteristics, the first ten error-free (based on onset/offset detection) strides within the recording period (last min of walking and running) were selected. Next, mean values of the stride characteristics across the two feet were calculated. Subsequently, a single mean of these values across the ten selected strides for each stride characteristic was calculated to be used in the further analysis.

2.6.3 FINGERTIP DISPLACEMENT (STUDY III)

The kinematic data for fingertip displacement were analysed using MATLAB version R2013a (The MathWorks, Inc., Natick, MA, USA). Only the vertical displacement was calculated. The maximum and minimum values of tapping movement were calculated using threshold detection techniques and verified manually by the experimenter. Then, average maximum and minimum values were calculated during the last 90 s of the tapping bout across the all analysed taps. Finally, the fingertip displacement (mm) was calculated by subtracting the average minimum from the average maximum.

3 RESULTS

This section presents a summary of the findings in the present Ph.D. project. For details, the reader is referred to the articles/manuscript (I-III).

3.1 EFFECT OF HEAVY STRENGTH TRAINING ON MAXIMAL STRENGTH (STUDY I-III)

In study (I) and (II), heavy hip strength training resulted in increases in 1RM for HET, HFT, and CON from pretest to posttest (33.6±13.2%, 28.1±13.0%, and 6.1±6.1%, respectively). The increases in 1RM were significantly larger in HET and HFT compared to CON (p= 0.001 and p=0.003, respectively) (Table 5). In study (III), 1RM extension and flexion in the training group increased 19.5±22.2% and 9.4±9.8%, respectively, from pretest to posttest (p=0.015 and p=0.001, respectively). Furthermore, 1RM extension in the training group was significantly larger than control at posttest (p=0.029) (Table 6).

***Table 5**: Results of 1RM at pretest and posttest in training (HET and HFT) and control groups in study I and II.*

Group	1RM at pretest (kg)	1RM at posttest (kg)
HET	46.9±12.5	62.3±11.0*
HFT	50.2±16.5	63.9±21.0*
Control	47.0±11.1	50.2±13.4

* Significant difference from pretest.

Table 6: *Results of 1RM (extension and flexion) at pretest and posttest in training and control groups in study III.*

Group	Pretest		Posttest	
	1RM extension (kg)	1RM flexion (kg)	1RM extension (kg)	1RM flexion (kg)
Training	1.1±0.3	3.3±1.2	1.3±0.4*	3.6±1.1*
Control	1.0±0.3	3.1±1.0	1.0±0.3	3.1±1.1

* Significant difference from pretest.

3.2 EFFECT OF HEAVY STRENGTH TRAINING ON FREELY CHOSEN MOVEMENT FREQUENCY (STUDY I-III)

In study (I), there was a significant effect of *time* on the absolute values of FCC in HET across the study period (p=0.005). The post hoc test showed lower cadence at test A1, A2, and A3 compared to pretest (p=0.017-0.033). Percentage reductions of FCC in HET compared to the corresponding changes in CON were significantly larger at test A1, A2, A3, and, posttest, with respect to pretest value (p=0.037). This was not the case when comparing HFT and CON (p=0.563) (Figure 7).

In study (II), despite increases in 1RM, heavy strength training did not affect the freely chosen stride rates during walking and running. Thus, there was no significant difference between each of the training groups and CON from the pretest to the subsequent tests (p=0.443 to 0.964).

In study (III), there was no significant effect of *group* on absolute values of freely chosen frequency during finger tapping (p=0.077). Unexpectedly, there was a significant effect of *time* on the freely chosen frequency (p=0.002). Data from both groups were collapsed and post hoc test showed that the tapping frequency at midtest (175.0±56.6 taps/min) and posttest (181.0±51.6 taps/min) were significantly larger (on average was around 11%) than the pretest value (163.0±52.0 taps/min) (p=0.005 and p=0.005, respectively). Additionally, tapping frequency was not significantly different between midtest and posttest (p=0.215).

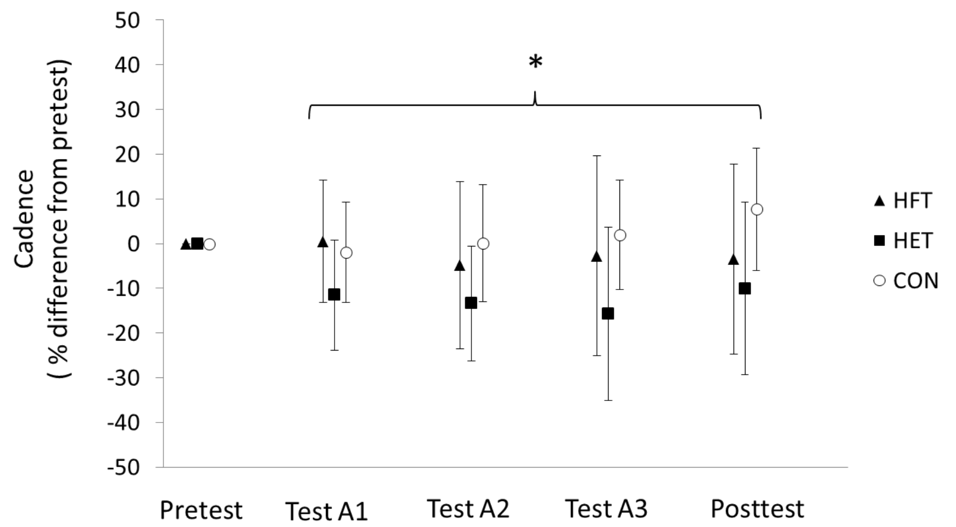

Figure 7*: Percentage changes from pretest values of cadence in training groups (HET and HFT), and control group (CON) at Pretest, test A1 (after one week of training), test A2 (after 2 weeks of training), test A3 (after 3 weeks of training), and posttest. *HET significantly different from CON (p=0.037). Modified from study (I).*

3.3 EFFECT OF HEAVY STRENGTH TRAINING ON RHYTHMIC MOVEMENT PATTERN (STUDY I-III)

In study (I), during cycling at freely chosen cadence, there was a significant effect of *time* on the absolute values of F_{min} and crank angle at F_{min} in HET (p=0.012 and p=0.001, respectively). Post hoc test revealed larger F_{min} at test A3 compared to the pretest value (p=0.031). This means that F_{min} became less negative after 3 weeks of training. Further, crank angle at F_{min} occurred later and was larger at test A2, A3, and posttest than pretest (p=0.009-0.025). The percentage increases in F_{min} in HET was significantly different than corresponding values in CON at test A1, A2, A3, and posttest with regard to pretest values (p=0.024). During cycling at 60 rpm cadence, there was no significant effect of time on the force profile characteristics in HET, HFT, and CON (p=0.077-0.930).

In study (II) and (III), the heavy strength training did not alter the rhythmic movement pattern characteristics during walking, running, and finger tapping (p=0.166-0.948).

3.4 WITHIN- AND BETWEEN-INDIVIDUAL VARIABILITY OF MOVEMENT FREQUENCIES (STUDY II)

The degree of within-individual steadiness of freely chosen stride rate during walking was shown by mean CI_{95} of 1.32 strides per min that was calculated across the participants, with a range from 0.48 to 4.06 strides per min. For comparison, during running, the mean CI_{95} was 1.95 strides per min with a range from 0.60 to 3.34 strides per min (Figure 8). Furthermore, less between-individual variability was found for freely chosen stride rates in walking and running (CV=4.46% and CV=5.45%, respectively) than for freely chosen pedalling rate in cycling (CV=14.84%).

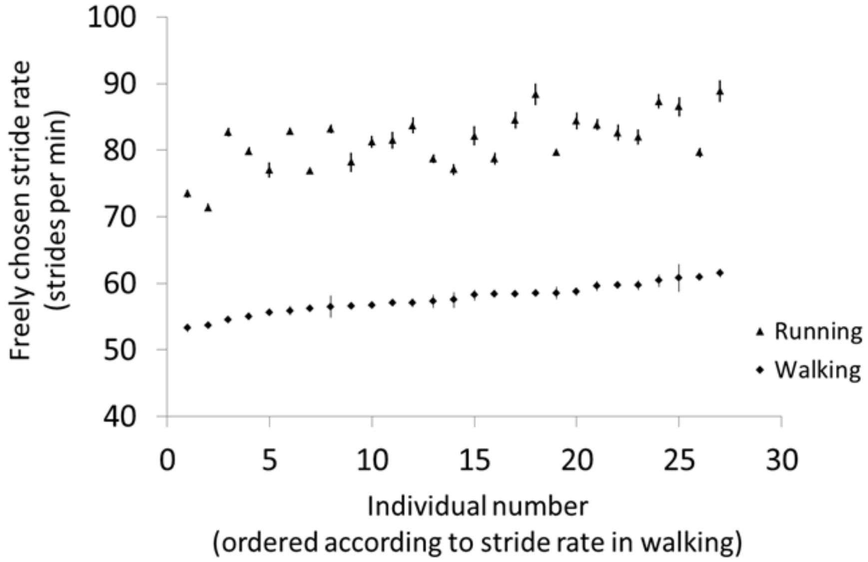

Figure 8*: Individual values of freely chosen stride rate. The data is presented as mean values across all tests, with 95% confidence interval bars. Further, data are ordered so that individual 1 is the one who had the lowest mean value during walking whereas individual 27 had the highest mean value etc***.**

3.5 PEARSON CORRELATION

Below, the correlations from studies I and II are presented. The rating regarding the size of *r* applies to both positive as well as negative correlations: 0.25 or lower is considered weak, 0.26-0.50 is moderate, 0.51-0.75 is fair and 0.76 or higher is high (Berg & Latin, 2008).

3.5.1 CORRELATION BETWEEN FREELY CHOSEN CADENCE (FCC) AND MAXIMAL STRENGTH (STUDY I)

For participants in HET group, the correlation coefficient was not significant between 1RM strength improvement and reduction in FCC from test A1 to posttest (p=0.253).

3.5.2 CORRELATION OF FREELY CHOSEN MOVEMENT FREQUENCY AT PRETEST BETWEEN WALKING, RUNNING AND CYCLING (STUDY II)

A fair correlation coefficient was observed between the freely chosen stride rate during walking at pretest with the corresponding data for running. However, the freely chosen pedalling rate in cycling was unrelated to the stride rates during locomotion. Further, the partial correlation coefficient between freely chosen stride rates during walking and running that eliminated the influence of variables of age, body height, body mass, and leg length continued to be fair (Table 7).

Table 7: Result of correlation analyses performed on pretest data.

Pearson correlation	Stride rate during walking		Stride rate during running	
	r	*P*	*r*	*P*
Stride rate during walking			0.72*	<0.001
Pedalling rate during cycling	0.16	0.219	0.04	0.424
Partial correlation				
Stride rate during walking			0.62*	0.001

*Significant correlation.

3.5.3 CORRELATION OF STRIDE CHARACTERISTICS BETWEEN WALKING AND RUNNING AT PRETEST (STUDY II)

A fair correlation coefficient was observed between walking and running at pretest for the durations of stance phase (r=0.58, p=0.002), swing phase (r=0.65, p<0.001), and the complete stride (r=0.72, p<0.001). The highest correlation coefficient was found for stride duration, which resembles the freely chosen stride rate (Figure 9).

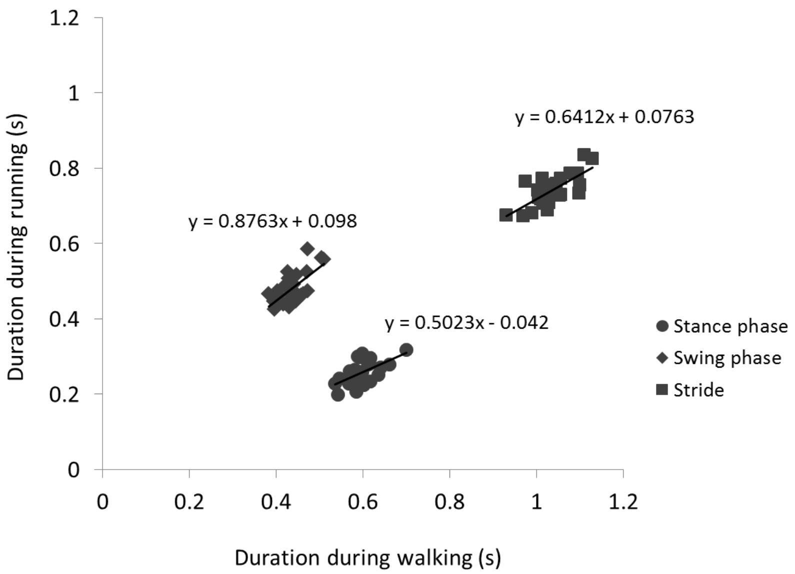

***Figure 9**: Relationship between duration of stance phase, swing phase, and stride during walking and running. Data is from the pretest. This figure is modified from study (II).*

4 DISCUSSION

The overall aim of this project was to provide new insights into the effect of strength training on aspects of rhythmic movement behaviour (frequency and pattern). Three studies were performed to improve the knowledge of nervous system organisation and function of different movement tasks. The main findings of these studies were: (1) Four weeks of heavy hip extension strength training, rather than heavy hip flexion strength training, reduced the FCC during submaximal cycling in recreationally active individuals. This reduction was found in the very early phase of the strength training period, that is, after one week of training (study I); (2) Despite increased maximal strength after 4 weeks of heavy strength training, there was no significant influence on stride characteristics during walking and running that was in contrast to the hypothesis of this study (study II); (3) No correlation was found between the freely chosen movement frequency in cycling and walking as well as in cycling and running while a positive correlation was found between walking and running (study II); (4) In contrast to previous results from cycling experiments, two weeks of heavy finger extension and flexion strength training did not influence the frequency and pattern of the freely chosen finger tapping (study III). Below, these findings are discussed in more details as well as the limitations and perspectives of the current thesis.

4.1 EFFECTS OF HEAVY STRENGTH TRAINING ON THE FREELY CHOSEN RHYTHMIC MOVEMENT FREQUENCY

The maximal strength in the present project increased in all studies for training group compared to the control group. Surprisingly, the strength training influenced only on the FCC during submaximal cycling (study I). It should be noticed that there was no correlation between strength improvement and reduction of the FCC in this study (study I) or in the study by Rønnestad et al. (Rønnestad et al. 2012). Therefore, it can be suggested that the muscle strength in itself is not a key factor affecting the FCC. It is most likely that the effects of strength training on other systems of body such as the nervous system can explain the reduction of FCC. Furthermore, it was observed that the heavy hip extension training reduced the cadence in recreationally active individuals after one week of training that was three weeks earlier than what has been reported before (Rønnestad et al. 2012). This fast reduction can be argued as an adaptation in the nervous system occurring in the primary phase of strength training (Gabriel et al. 2006). Therefore, the reduction of FCC following strength training in study (I) is likely caused by the alterations in neural factors (i.e., decreased central motor drive during submaximal exercise, decreased net excitability of the CPG, reduced inhibitory feedback) that are mentioned in section 1-3 (Hansen et al. 2007; Rønnestad et al. 2012).

A half-centre (one half for flexor activation, one half for extensor) model has been suggested that resided in the lumbar spinal cord and is responsible for generating the basic locomotor rhythm and muscle activity (Brown, 1911; Zehr, 2005). According to this model, fine coordination of muscle activity during locomotion caused by relations within and between flexor and extensor half-centres of a given limb (Orlovsky et al. 1999). In study (I), the reductions in the cadence after strength training in HET, while not in HFT, may propose that half-center for extensor activation was more influenced by training.

According to the common core hypothesis that suggests that the same central neural networks, consisting of CPGs, generate the freely chosen frequency during different rhythmic movements (Zehr, 2005), it was supposed that the movement frequency during walking and running would be influenced by strength training in the same way as pedalling frequency. However, it was not observed in study (II). To discuss the results, it appears that walking and running are evolutionary consolidated forms of locomotion (Martin et al. 2000; McNeill Alexander, 2002; Zarrugh & Radcliffe, 1978) that have been performed from the beginning of evolution and the neural networks for controlling these movements are genetically consolidated in parallel. This notion is supported by the observations of spontaneous stepping in new-born and in infants (Dominici et al. 2011; Yang et al. 1998). Therefore, likely due to the evolutionary consolidation during walking and running, these movements are controlled robustly and less sensitive to the alterations in the descending and afferent inputs than the movement control during cycling.

The proposed evolutionary consolidation control of locomotion is supported in the present study by lower between-individual variation of freely chosen frequency during walking and running compared with cycling. Further, the steadiness of the freely chosen movement frequency during locomotion is supported by steady freely chosen stride rates throughout the study period and lower within-individual variation of freely chosen frequency during walking and running compared with cycling, i.e. 5 to 13 rpm (Hansen & Ohnstad, 2008).

In study (III), heavy strength training was performed for 2 weeks, since the freely chosen frequency reduced after one week of training in the first study. The results of this study showed that two weeks of heavy index finger strength training did not alter the freely chosen tapping frequency. This finding contrasted the hypothesis, which was formulated on the basis of previous results from cycling experiments. A number of differences in the task specificity between finger tapping and cycling might be an explanation for the current finding (see section 4.3). Furthermore, the different location of the motor neurons at the central nervous system which are involved in the activation of finger and legs (Balter & Zehr, 2007; Duysens & Van de Crommert, 1998; Juvin et al. 2005; Wannier et al. 2001) may explain the discrepancies in the modulation of the frequency of index finger tapping and pedalling. This notion can be supported by a previous finding of no correlation between finger tapping frequency and freely chosen pedaling rate during cycling (Hansen & Ohnstad, 2008).

4.2 EFFECTS OF HEAVY STRENGTH TRAINING ON THE RHYTHMIC MOVEMENT PATTERN

In study (I), minimum tangential pedal force (F_{min}) and crank angle at F_{min} were changed during FCC after hip extension strength training while not after hip flexion training. It may suggest that the half-center for extensor activation was more influenced by training as movement frequency also changed after hip extension training. Furthermore, since the tangential pedal force during cycling at 60 rpm was not influenced by strength training, it was proposed that the observed changes in HET were more a consequence of changed cadence than a result of movement pattern alteration in itself. In line with the present results, it has been observed that the peak negative crank torque (reflecting tangential pedal force in this study) is getting less negative and occurs later in the crank cycle systematically as cadence is reduced (Neptune & Herzog, 1999). Considering the reduction in FCC, it would expect to see a slower movement that is easier for individuals to coordinate the pedaling movement including lifting the leg in the upstroke phase during cycling. However, there were no alterations in the movement pattern during walking and running in this project. Therefore, it seems that the effect of the neuronal changes as a result of strength training on the control of CPG during cycling was strong enough to decrease the FCC and subsequently changed the movement pattern. While in study (II), the movement patterns during walking and running probably genetically generate by the central neural networks that cause to be less sensitive to variations in the nervous system after strength training. In addition, the partial differences in the neural networks due to further functional layers that are added in the CPGs during development from childhood (Lacquaniti et al. 2013) may explain the different observations in the control of locomotion in comparison with cycling. Therefore, walking and running most likely induce activity in different layers of the CPGs than cycling.

Furthermore, the constancy in kinetic and kinematic characteristics presenting the movement pattern during finger tapping was observed after strength training in study (III). These results are in contrast to previous observations showing the alterations in the movement pattern after strength training during submaximal cycling in study (I). Moreover, it has been reported that strength training influenced on the movement pattern in the form of increasing the passive knee joint range of motion that was presumably caused by extending the muscle fascicles (Potier et al. 2009). Additionally, increasing in RFD after strength training has been reported as a result of increased afferent neural drive to the trained muscles (Aagaard et al. 2000; Vangsgaard et al. 2014). On the contrary, no effect of strength training on the movement pattern as well as frequency was observed during finger tapping that could indicate any alteration in the muscle activation profile. However, an alteration in the rhythmic movement pattern associated with constant movement frequency is actually possible (Hansen et al. 2014). The later could be due to the two different components of CPG that are responsible for generating the rhythmic movement; one for rhythmic movement frequency and the other for rhythmic movement pattern (Dominici et al. 2011; Kriellaars et al. 1994; McCrea & Rybak, 2008; Perret & Cabelguen, 1980). Therefore, based on the results from study (II) and (III), it could be speculated that none of these components of CPGs were affected by strength training during walking, running, and finger tapping.

4.3 COMPARISON OF TASKS OF PEDALLING, LOCOMOTION AND FINGER TAPPING

In the present project, different results in study (II) and (III) were obtained compared to study (I). These results may partly be a consequence of the specific afferent input, which is received by the central nervous system (and the CPG) during pedalling, locomotion, and finger tapping). In cycling, the number of movement degrees of freedom is reduced compared to walking and running, because body movements are constrained by the bicycle. Thus, the legs are fixed in planar closed chain movements, the hip movements are constrained by sitting in the saddle, and the arms and upper body movements are constrained by holding the handlebar, thereby also constraining the coupling between upper and lower extremity movements. In addition, the postural demands in cycling are different due to the fewer movement degrees of freedom and less weight bearing than locomotion.

Walking and running supposedly are evolutionary and also genetically predetermined as preferred forms of locomotion and since these locomotor movement patterns supposedly are controlled by the same central neural networks, it may seem logical that the voluntary movement frequency during walking is related to running as was observed as a significant and positive correlation. Consequently, cycling must be as a developed movement task from infant to adult without the same type of evolutionary optimisation, and under the control of a neural network that is optimised to the control of walking and running. In support of this suggestion, it has been shown that the freely chosen stride rate during walking and running are closely optimised with regard to movement economy (Cavanagh & Williams, 1982; de Ruiter et al. 2014; Zarrugh & Radcliffe, 1978). This is not the case during submaximal cycling where the FCC (70-90 min^{-1} in the current study) is markedly higher than energetically economical pedalling rate (50-60 min^{-1}) (Foss & Hallén, 2005; Hansen et al. 2006; Hansen & Ohnstad, 2008; Marsh et al. 2000; Marsh & Martin, 1997; Martin et al. 2000; Nielsen et al. 2004). Therefore, the behaviour of the leg movements under CPG influence during cycling i.e. the freely chosen pedalling rate may not necessarily be strictly correlated to the freely chosen stride rates in walking and running. This is in line with the lack of significant correlation between the freely chosen movement frequencies during cycling and walking/running, respectively, in the present project. In addition, this lack of correlation may be partly due to the different postural demands during cycling than walking and running that make different descending and the afferent inputs to the same neural networks.

Furthermore, the differences between finger tapping and cycling may be a reason for the differences between present results. Finger tapping in study (III) was performed for one finger on the right hand. The index finger represents only a small segment of the right arm while cycling involves both legs. Further, the amount of trained muscle mass is different between these two tasks. Also, there is a difference in external load when comparing finger tapping and cycling. Finger tapping was performed without additional external load, while cycling in study (I) performed at a constant power output, i.e., 100 W. Therefore, it is conceivable that the neural network during finger tapping receives a different pattern of both descending and the afferent input than cycling.

In addition, the freely chosen frequency during finger tapping was influenced by *time* across the present study despite a familiarisation session. That is, both training and control group tapped faster at the midtest and posttest rather than the pretest. Interestingly, such increasing has not been observed for finger tapping frequency across 12 weeks (Hansen & Ohnstad, 2008). The lack of alteration in the finger tapping frequency in the latter study might be due to the differences in the methodological detail. In the present study, participants performed the finger tapping every week versus every 2 weeks in the study by Hansen and Ohnstad (Hansen & Ohnstad, 2008). Therefore, it can be considered that the length of retention periods has an important role even for simple, automated and submaximal tasks.

4.4 LIMITATIONS AND PERSPECTIVES

This thesis has focused on the rhythmic movement's behaviour after strength training. It is acknowledged that the present thesis did not apply evaluation of neuromuscular and morphological adaptation and brain, e.g. in the form of muscle activation or brain activity measurements. In other words, such assessments, e.g. by electromyography and magnetic resonance imaging, can be used to elucidate the potential mechanisms that may be important for the observed alterations in rhythmic movement (Vangsgaard et al. 2014). Still, we are limited for investigating the effects of the CPG on voluntary rhythmic movement in humans. Therefore, studies like the present thesis are needed for advancing the understanding of the movement behaviour during human rhythmic movements.

Another limitation of this project is that the strength training in study (III) was performed for only two weeks. It could be claimed that this period was too short to change the movement behaviour. However, in study (I) a considerable reduction in FCC was observed after one week of training.

In the present project, only healthy and recreationally active individuals were included. The results could have been different in a population with musculoskeletal disorders. Since, the maintenance or improvement of motor performance among healthy and injured individuals is a common goal in exercise and rehabilitation programmes; therefore, it will be necessary to perform further studies in order to extrapolate the present findings to other populations.

5 CONCLUSION

The present project showed that heavy hip extension strength training rather than heavy hip flexion strength training caused to decrease the FCC during submaximal cycling. This reduction was observed during a very early adaptation phase to training that is after one week. Furthermore, hip extension strength training caused to alter the movement pattern during submaximal cycling by changing the F_{min} and crank angle at F_{min}. On the contrary, heavy strength training did not alter the freely chosen stride rate and stride phase characteristics during walking and running. Further, a significant correlation was found between freely chosen stride rates during walking and running while it was not the case between stride rates during walking and running, respectively, and the pedalling rate. Since the same neural networks have been suggested to generate the freely chosen frequency during different rhythmic movements, therefore, the reason for the lack of correlation may be a consequence of the different postural demands between walking, running, and cycling. Finally, considering the fact that cycling is a movement skill developed from childhood compared to walking and running which likely are evolutionary consolidation forms of locomotion, it was proposed that pedalling movements to be generated by neural networks that genetically consolidated for locomotion. Furthermore, the kinetic and kinematic characteristics during finger tapping were unchanged after two weeks of heavy finger extension and flexion that was in contrast to the previous results of decreased frequency and altered movement pattern during cycling. Unexpectedly, the freely chosen tapping frequency increased across the study period. Therefore, different neural networks controlling various rhythmic movements and the differences in the task specificity most likely explain the dissimilarity in the present findings.

6 THESIS AT A GLANCE

	Primary aim	Method	Main finding
Study I			
	To investigate the temporal effects of separate hip extension and flexion on rhythmic movement frequency and pattern during submaximal pedalling.	Measuring 1RM at pretest and posttest, and measuring the FCC and tangential pedal force profile every week. *Intervention*: 4 weeks heavy hip extension and flexion strength training.	1RM increased after 4 weeks of training. FCC decreased already after one week of training. And merely after hip extension training. F_{min} and crank angle at F_{min} changed after hip extension training.
Study II			
	To determine the relationship between the freely chosen frequencies during walking, running, and cycling. Also to investigate the effects of heavy strength training on stride phase characteristics during locomotion.	Measuring the freely chosen stride rate and stride phase characteristics during walking and running every week across the study period. *Intervention*: 4 weeks heavy hip extension and flexion strength training.	Positive correlation was observed between freely chosen stride rates during walking and running, while not between freely chosen frequencies in cycling and locomotion. Heavy strength training did not alter the stride characteristics during walking and running.
Study III			
	To investigate the effects of heavy strength training on the kinetic and kinematic characteristics during index finger tapping.	Measuring the freely chosen tapping frequency and dynamic characteristics during finger tapping every week across the study period. *Intervention*: 2 weeks right finger extension and flexion strength training.	Finger tapping characteristics remained unchanged after strength training. The freely chosen finger tapping frequency increased around 11% across the 2 weeks study period.

7 REFERENCES

Aagaard, P., Simonsen, E., Andersen, J., Magnusson, S., Halkjaer-Kristensen, J., & Dyhre-Poulsen, P. (2000). Neural inhibition during maximal eccentric and concentric quadriceps contraction: Effects of resistance training. *Journal of Applied Physiology, 89*, 2249-2257.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Neural adaptation to resistance training: Changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology, 92*, 2309-2318.

Balter, J. E., & Zehr, E. P. (2007). Neural coupling between the arms and legs during rhythmic locomotor-like cycling movement. *Journal of Neurophysiology, 97*, 1809-1818.

Barroso, F., Torricelli, D., Moreno, J. C., Taylor, J., Gomez-Soriano, J., Esteban, E. B., piazza, S., Santos, C., & Pons, J. L. (2014). Shared muscle synergies in human walking and cycling. *Journal of Neurophysiology, 112*, 1984-1998.

Berg, K.E., & Latin, R.W. (2008). Essentials of research methods in health, physical education, exercise science, and recreation. Lippincott Williams & Wilkins, p. 124-128.

Brown, T. G. (1911). The intrinsic factors in the act of progression in the mammal. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character, 84*, 308-319.

Calancie, B., Needham-Shropshire, B., Jacobs, P., Willer, K., Zych, G., & Green, B. A. (1994). Involuntary stepping after chronic spinal cord injury. evidence for a central rhythm generator for locomotion in man. *Brain : A Journal of Neurology, 117*, 1143-1159.

Cambach, W., Chadwick-Straver, R. V., Wagenaar, R. C., van Keimpema, A. R., & Kemper, H. C. (1997). The effects of a community-based pulmonary rehabilitation programme on exercise tolerance and quality of life: A randomized controlled trial. *The European Respiratory Journal, 10*, 104-113.

Cappellini, G., Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2006). Motor patterns in human walking and running. *Journal of Neurophysiology, 95*, 3426-3437.

Carroll, T. J., Selvanayagam, V., Riek, S., & Semmler, J. (2011). Neural adaptations to strength training: Moving beyond transcranial magnetic stimulation and reflex studies. *Acta Physiologica, 202*, 119-140.

Carroll, T. J., Riek, S., & Carson, R. G. (2002). The sites of neural adaptation induced by resistance training in humans. *The Journal of Physiology, 544*, 641-652.

Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise, 14*, 30-35.

Delecluse, C. (1997). Influence of strength training on sprint running performance. *Sports Medicine, 24*, 147-156.

De Luca, C. J., & Erim, Z. (1994). Common drive of motor units in regulation of muscle force. *Trends in Neurosciences, 17*, 299-305.

de Ruiter, C. J., Verdijk, P. W., Werker, W., Zuidema, M. J., & de Haan, A. (2014). Stride frequency in relation to oxygen consumption in experienced and novice runners. *European Journal of Sport Science, 14*, 251-258.

Dennerlein, J. T., Mote Jr, C., & Rempel, D. M. (1998). Control strategies for finger movement during touch-typing the role of the extrinsic muscles during a keystroke. *Experimental Brain Research, 121*, 1-6.

Dietz, V., Colombo, G., & Jensen, L. (1994). Locomotor activity in spinal man. *The Lancet, 344*, 1260-1263.

Dimitrijevic, M. R., Gerasimenko, Y., & Pinter, M. M. (1998). Evidence for a spinal central pattern generator in humans. *Annals of the New York Academy of Sciences, 860*, 360-376.

Dominici, N., Ivanenko, Y. P., Cappellini, G., d'Avella, A., Mondì, V., Cicchese, M., Fabiano, A., Silei, T., Di Paolo, A., Giannini, C., Poppele, R. E., Lacquaniti, F. (2011). Locomotor primitives in newborn babies and their development. *Science, 334*, 997-999.

Duysens, J., & Van de Crommert, Henry WAA. (1998). Neural control of locomotion; part 1: The central pattern generator from cats to humans. *Gait & Posture, 7*, 131-141.

Falvo, M. J., Sirevaag, E. J., Rohrbaugh, J. W., & Earhart, G. M. (2010). Resistance training induces supraspinal adaptations: Evidence from movement-related cortical potentials. *European Journal of Applied Physiology, 109*, 923-933.

Fedirchuk, B., Nielsen, J., Petersen, N., & Hultborn, H. (1998). Pharmacologically evoked fictive motor patterns in the acutely spinalized marmoset monkey (callithrix jacchus). *Experimental Brain Research, 122*, 351-361.

Foss, Ø., & Hallén, J. (2005). Cadence and performance in elite cyclists. *European Journal of Applied Physiology, 93*, 453-462.

Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise. *Sports Medicine, 36*, 133-149.

Goulding, M. (2009). Circuits controlling vertebrate locomotion: Moving in a new direction. *Nature Reviews Neuroscience, 10*, 507-518.

Grillner, S., & Zangger, P. (1979). On the central generation of locomotion in the low spinal cat. *Experimental Brain Research, 34*, 241-261.

Hansen, E. A., Ebbesen, B. D., Dalsgaard, A., Mora-Jensen, M. H., & Rasmussen, J. (2015). Freely chosen index finger tapping frequency is increased in repeated bouts of tapping. *Journal of Motor Behaviour*, Epup ahead of print.

Hansen, E. A., Jensen, K., & Pedersen, P. K. (2006). Performance following prolonged sub-maximal cycling at optimal versus freely chosen pedal rate. *European Journal of Applied Physiology, 98*, 227-233.

Hansen, E. A., & Ohnstad, A. E. (2008). Evidence for freely chosen pedalling rate during submaximal cycling to be a robust innate voluntary motor rhythm. *Experimental Brain Research, 186*, 365-373.

Hansen, E. A., Raastad, T., & Hallén, J. (2007). Strength training reduces freely chosen pedal rate during submaximal cycling. *European Journal of Applied Physiology, 101*, 419-426.

Hansen, E. A., Voigt, M., Kersting, U. G., & Madeleine, P. (2014). Frequency and pattern of rhythmic leg movement in humans after fatiguing exercises. *Motor Control, 18, 297-309.*

Hartley, G. L., & Cheung, S. S. (2013). Freely chosen cadence during a covert manipulation of ambient temperature. *Motor Control, 17*, 34-47.

Jindrich, D. L., Zhou, Y., Becker, T., & Dennerlein, J. T. (2003). Non-linear viscoelastic models predict fingertip pulp force-displacement characteristics during voluntary tapping. *Journal of Biomechanics, 36*, 497-503.

Juvin, L., Simmers, J., & Morin, D. (2005). Propriospinal circuitry underlying interlimb coordination in mammalian quadrupedal locomotion. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience, 25*(25), 6025-6035.

Keen, D. A., & Fuglevand, A. J. (2004). Common input to motor neurons innervating the same and different compartments of the human extensor digitorum muscle. *Journal of Neurophysiology, 91*, 57-62.

Kiehn, O. (2006). Locomotor circuits in the mammalian spinal cord. *Annual Review of Neuroscience, 29*, 279-306.

Kriellaars, D., Brownstone, R., Noga, B., & Jordan, L. (1994). Mechanical entrainment of fictive locomotion in the decerebrate cat. *Journal of Neurophysiology, 71*, 2074-2086.

Lacquaniti, F., Ivanenko, Y. P., d'Avella, A., Zelik, K. E., & Zago, M. (2013). Evolutionary and developmental modules. *Frontiers in Computational Neuroscience, 7*, 1-6.

Lee, D. L., Kuo, P., Jindrich, D. L., & Dennerlein, J. T. (2009). Computer keyswitch force–displacement characteristics affect muscle activity patterns during index finger tapping. *Journal of Electromyography and Kinesiology, 19*, 810-820.

Li, L., van den Bogert, Elizabeth CH, Caldwell, G. E., van Emmerik, R. E., & Hamill, J. (1999). Coordination patterns of walking and running at similar speed and stride frequency. *Human Movement Science, 18*, 67-85.

MacLellan, M., Qaderdan, K., Koehestanie, P., Duysens, J., & McFadyen, B. (2012). Arm movements during split-belt walking reveal predominant patterns of interlimb coupling. *Human Movement Science, 32, 79-90.*

Marsh, A. P., Martin, P. E., & Foley, K. O. (2000). Effect of cadence, cycling experience, and aerobic power on delta efficiency during cycling. *Medicine and Science in Sports and Exercise, 32*, 1630-1634.

Marsh, A. P., & Martin, P. E. (1997). Effect of cycling experience, aerobic power, and power output on preferred and most economical cycling cadences. *Medicine and Science in Sports and Exercise, 29*, 1225-1232.

Martin, P., Sanderson, D., & Umberger, B. (2000). Factors affecting preferred rates of movement in cyclic activities. *Biomechanics in Sport: Performance Enhancement and Injury Prevention,* 142-160.

McCrea, D. A., & Rybak, I. A. (2008). Organization of mammalian locomotor rhythm and pattern generation. *Brain Research Reviews, 57*, 134-146.

McNeill Alexander, R. (2002). Energetics and optimization of human walking and running: The 2000 raymond pearl memorial lecture. *American Journal of Human Biology, 14*, 641-648.

Minassian, K., Persy, I., Rattay, F., Pinter, M., Kern, H., & Dimitrijevic, M. (2007). Human lumbar cord circuitries can be activated by extrinsic tonic input to generate locomotor-like activity. *Human Movement Science, 26*, 275-295.

Moussay, S., Dosseville, F., Gauthier, A., Larue, J., Sesboüe, B., & Davenne, D. (2002). Circadian rhythms during cycling exercise and finger-tapping task. *Chronobiology International, 19*, 1137-1149.

Neptune, R., & Herzog, W. (1999). The association between negative muscle work and pedaling rate. *Journal of Biomechanics, 32*, 1021-1026.

Nielsen, J. S., Hansen, E. A., & Sjøgaard, G. (2004). Pedalling rate affects endurance performance during high-intensity cycling. *European Journal of Applied Physiology, 92*, 114-120.

Nilsson, J., & Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica Scandinavica, 136*, 217-227.

Orlovsky, G. N., Deliagina, T., Grillner, S., Orlovskii, G., & Grillner, S. (1999). *Neuronal control of locomotion: From mollusc to man*. New York: Oxford University Press Inc.

Perret, C., & Cabelguen, J. (1980). Main characteristics of the hindlimb locomotor cycle in the decorticate cat with special reference to bifunctional muscles. *Brain Research, 187*, 333-352.

Potier, T. G., Alexander, C. M., & Seynnes, O. R. (2009). Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *European Journal of Applied Physiology, 105*, 939-944.

Reilly, K. T., Nordstrom, M. A., & Schieber, M. H. (2004). Short-term synchronization between motor units in different functional subdivisions of the human flexor digitorum profundus muscle. *Journal of Neurophysiology, 92*, 734-742.

Rønnestad, B. R., Hansen, E. A., & Raastad, T. (2012). Strength training affects tendon cross-sectional area and freely chosen cadence differently in noncyclists and well-trained cyclists. *The Journal of Strength & Conditioning Research, 26*, 158-166.

Rønnestad, B. R., Hansen, E. A., & Raastad, T. (2010). In-season strength maintenance training increases well-trained cyclists' performance. *European Journal of Applied Physiology, 110*, 1269-1282.

Sale, D., Upton, A., McComas, A., & MacDougall, J. (1983). Neuromuscular function in weight-trainers. *Experimental Neurology, 82*, 521-531.

Sasaki, K., & Neptune, R. R. (2006). Differences in muscle function during walking and running at the same speed. *Journal of Biomechanics, 39*, 2005-2013.

Shima, K., Tamura, Y., Tsuji, T., Kandori, A., & Sakoda, S. (2011). A cpg synergy model for evaluation of human finger tapping movements. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, 4443-4448.

So, R. C., Ng, J. K., & Ng, G. Y. (2005). Muscle recruitment pattern in cycling: A review. *Physical Therapy in Sport, 6*, 89-96.

Sternad, D., Dean, W. J., & Newell, K. M. (2000). Force and timing variability in rhythmic unimanual tapping. *Journal of Motor Behaviour, 32*, 249-267.

Teo, W., Rodrigues, J., Mastaglia, F., & Thickbroom, G. (2013). Comparing kinematic changes between a finger-tapping task and unconstrained finger flexion–extension task in patients with Parkinson's disease. *Experimental Brain Research, 227*, 323-331.

Van de Crommert, Henry WAA, Mulder, T., & Duysens, J. (1998). Neural control of locomotion: Sensory control of the central pattern generator and its relation to treadmill training. *Gait & Posture, 7*, 251-263.

Vangsgaard, S., Taylor, J. L., Hansen, E. A., & Madeleine, P. (2014). Changes in H reflex and neuromechanical properties of the trapezius muscle after 5 weeks of eccentric training: A randomized controlled trial. *Journal of Applied Physiology, 116*, 1623-1631.

Walker, S., Peltonen, J., Ahtiainen, J. P., Avela, J., & Häkkinen, K. (2009). Neuromuscular fatigue induced by an isotonic heavy-resistance loading protocol in knee extensors. *Journal of Sports Sciences, 27*, 1271-1279.

Wannier, T., Bastiaanse, C., Colombo, G., & Dietz, V. (2001). Arm to leg coordination in humans during walking, creeping and swimming activities. *Experimental Brain Research, 141*(3), 375-379.

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Sports Medicine, 38,* 285-288.

Yang, J. F., Stephens, M. J., & Vishram, R. (1998). Infant stepping: A method to study the sensory control of human walking. *The Journal of Physiology, 507*, 927-937.

Zarrugh, M., & Radcliffe, C. (1978). Predicting metabolic cost of level walking. *European Journal of Applied Physiology and Occupational Physiology, 38*, 215-223.

Zehr, E. P. (2005). Neural control of rhythmic human movement: The common core hypothesis. *Exercise and Sport Sciences Reviews, 33*, 54-60.

Zehr, E. P., & Duysens, J. (2004). Regulation of arm and leg movement during human locomotion. *The Neuroscientist, 10*, 347-361.

Zehr, E. P., Balter, J. E., Ferris, D. P., Hundza, S. R., Loadman, P. M., & Stoloff, R. H. (2007). Neural regulation of rhythmic arm and leg movement is conserved across human locomotor tasks. *The Journal of Physiology, 582*, 209-227.

Zentgraf, K., Lorey, B., Bischoff, M., Zimmermann, K., Stark, R., & Munzert, J. (2009). Neural correlates of attentional focusing during finger movements: A fMRI study. *Journal of Motor Behaviour, 41*, 535-541.

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