USE OF DEEPER PLANTAR FLEXOR MUSCLES IN LOW TORQUE ISOMETRIC AND CONCENTRIC PLANTAR FLEXION TASKS

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ABSTRACT

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Coordination of a task such as plantar flexion might seem simple, but is in reality achieved through the activation of several muscles—muscles that play an important role in locomotion and posture control. These can be divided in to two groups, superficial and deep plantar flexors. It has been shown that although people usually produce certain well learned movements very similarly, some variability in the coordination might occur. This is also the case with the ankle plantar flexors as shown by Finni et al. (2006) and Masood et al (2014). Purpose of the study was to examine whether some individuals use their deeper plantar flexors to a greater extent than others and to see whether the relative contribution of the deeper muscles is affected by the type of movement or torque level. The two methods of measuring muscle activity, EMG and VE-PC MRI, were also compared.

Fifteen subjects took part in two measurement sessions where the activity of the plantar flexor muscles was measured. The first session took place in a biomechanics laboratory where EMG data from gastrocnemius medialis, soleus and flexor hallucis longus was recorded. The other session was done in the MRI scanner and produced muscle tissue velocity data for the same three muscles. Subjects did both isometric and concentric plantar flexion tasks at torque levels of 10% MVC and 30% MVC.

The relative contribution of the deeper muscles was assessed by calculating velocity ratios between GM and FHL as well as Sol and FHL. Clear differences were found between individuals. The lowest ratios, indicating greater activity of deep muscles were 1.02 for GM/FHL and 1.09 for Sol/FHL, whereas, the highest ratios were 2.08 and 2.44 respectively. At 10% torque level the two different movement types differed slightly. For GM/FHL velocity ratio was 0.41 ($p<0.05$), and for Sol/FHL 0.38 ($p=0.68$) smaller in isometric task compared to concentric. Torque level had no effect on the relative contribution of the deeper muscles. For GM ($r=0.52$, $p<0.001$) and FHL ($r=0.59$, $p<0.001$) there was a correlation between the EMG and peak mean negative velocity. The correlation between peak mean negative velocity and torque, and EMG and torque were also similar to each other.

Differences in velocity ratios show that individuals use their deeper plantar flexors to different extent. Some of the subjects showed little to no movement in the deeper muscles whereas others had equal peak mean velocities in the deeper muscles. With the conflicting results no clear conclusion can be drawn on whether torque or type of movement affect the relative contribution of the deeper muscles. The two measurement methods yielded similar results and there was also a correlation between peak mean velocity and EMG for GM and FHL.

Key words: Plantar flexion, coordination, velocity encoded phase contrast magnetic resonance imaging (VE-PC MRI), electromyography (EMG).

ABBREVIATIONS

CNS	Central nervous system
EMG	Electromyography
FHL	Flexor hallucis longus
GM	Gastrocnemius medialis
MRI	Magnetic resonance imaging
MVC	Maximum voluntary contraction
PC MRI	Phase contrast MRI
ROI	Region of interest
SD	Standard deviation
Sol	Soleus
VE-PC MRI	Velocity encoded phase contrast

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1 INTRODUCTION

Large number of degrees of freedom and even larger number of muscles in a human body makes coordinating movements very complex. In theory there is an infinite number of ways to perform a motor task, still individuals usually perform a certain task very similarly. In most cases the goal of a motor task is achieved by using a few agonistic muscles in a coordinated fashion to produce torque in a given joint. It has been shown, however, that some variation exists between individuals regarding which muscles are used and what is the relative contribution of each muscle towards the net torque (Finni et al 2003, Masood et al. 2014).

Plantar flexion of the ankle joint is one of the motor tasks that requires the coordinated interplay of several muscles in order to produce a desired torque over the ankle joint. Muscles responsible for plantar flexion of the ankle are an important group of muscles for locomotion and posture control. They are situated in the lateral compartment of the leg and can be divided into two groups, superficial, and deep plantar flexors. Most important of the plantar flexors are the superficial gastrocnemius medialis, gastrocnemius lateralis and soleus, all of which connect to the calcaneus trough the common achilles tendon. According to research triceps surae muscles produce 65 to 85 percent of the plantar flexion torque (Gregor et al. 1991, Zandwijk et al. 1998). Remainder is produced by the deep muscles, strongest of which is flexor hallucis longus.

In order to gain an insight into the relative contribution of different muscles during plantar flexion it is important to be able to also measure the activity of the deeper musculature. Electromyography (EMG) has for long been the most widely used method of assessing activity of muscles. It is however not possible to measure EMG from deeper muscles noninvasively. Imaging techniques such as velocity encoded phase contrast magnetic resonance imaging (VE PC MRI) offer a solution to noninvasively asses the activity of both superficial and deeper muscles by measuring the velocity of muscle tissue during the contraction cycle.

2 PRODUCTION OF MOVEMENT

Both voluntary and involuntary movements are produced by spatial and temporal contractions of skeletal muscles controlled by different parts of the central nervous system (CNS). The motor systems, therefore, plan, coordinate, and execute movement. Some of the movements require remarkable level of motor skill, but once learned the motor systems can reproduce the movements with relative ease and for the most part automatically. (Kandel et al. 2000, 653; Purves et al. 2001, 346.)

2.1 Central control

Central nervous system consists of the brain and the spinal cord. The brain can be divided into six major regions (Figure 1); the cerebral hemispheres, diencephalon, cerebellum and, the brainstem formed by the medulla, pons and, midbrain. Together with the spinal cord the six regions form the seven major divisions of the CNS. The most important role of the central nervous system is to control the various activities of the body. These activities include the secretion of exocrine and endocrine glands, contraction of the smooth muscles, and the contraction of skeletal muscles. (Gyuton & Hall 2000, 512.)

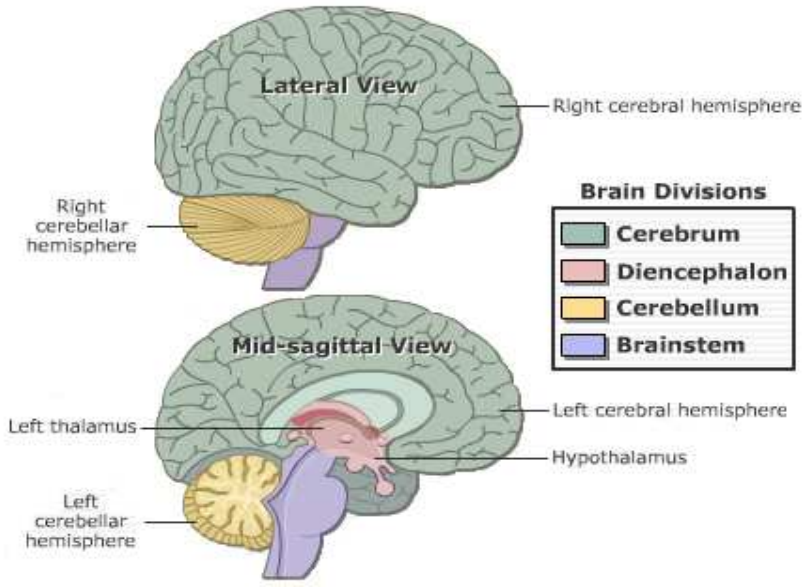

FIGURE 1. The major divisions of the brain. (Get Body Smart 2009.)

A coordinated motor task involves the contractions of task specific muscles, or parts of muscles, with appropriate force and with correct timing. In order to achieve this multiple parts of the CNS take part in the control of the skeletal muscle, each of them playing a specific role. Higher regions are primarily concerned with deliberate movements that are controlled by the thought processes of the cerebrum, whereas lower regions control the automatic and instantaneous motor responses caused by sensory stimuli. (Gyuton & Hall 2000, 512.)

2.1.1 Spinal Cord

Spinal cord is the lowest part of the CNS, and also the simplest. It has two major functions; on one hand it transmits sensory (afferent) information from peripheral sources such as skin, joints, and muscles to the higher levels of the CNS, on the other hand, it transmits the command signals from the higher levels back to the periphery. Spinal cord is also called the final common pathway, since all the commands for movement, whether reflexive or voluntary, are conveyed to the muscles through α motor neurons, cell bodies of which, are located in the ventral horn of the spinal cord grey matter. The α-motor neurons are somatotopically organized within the ventral horn (Figure 2). Neurons innervating axial muscles are located in the medial part and the ventral horn, whereas, neurons innervating distal limb muscles are located in the lateral part of the ventral horn. (Latash 1998, 151; Shumway-Cook & Wollacott 2001, 51; Purves et al. 2001, 346.)

The importance of the spinal cord for the control of muscles is obvious, since, without the connections made by the spinal cord no signals can get through to the muscles. Spinal cord, however, does not act just as a transmitting pathway between the periphery and the brain. The intermediate zone of the spinal cord houses spinal interneurons that form local neural networks within the spinal cord (Figure 2). Interneurons receive inputs from the higher motor centres, as well as, the sensory neurons; and form connections with the α-motor neurons. They can span across several spinal segments and terminate bilaterally. Because of the connections that the interneurons have and the circuits they form, the spinal cord is also involved in the initial reception and processing of the somatosensory information. Local circuitry also plays an important role in motor coordination because of their ability to control timing and coordination of

complex motor behaviours such as walking, and also adjusting them in response to altered circumstances. (Latash 1998, 151; Shumway-Cook & Wollacott 2001, 51; Purves et al. 2001, 346.)

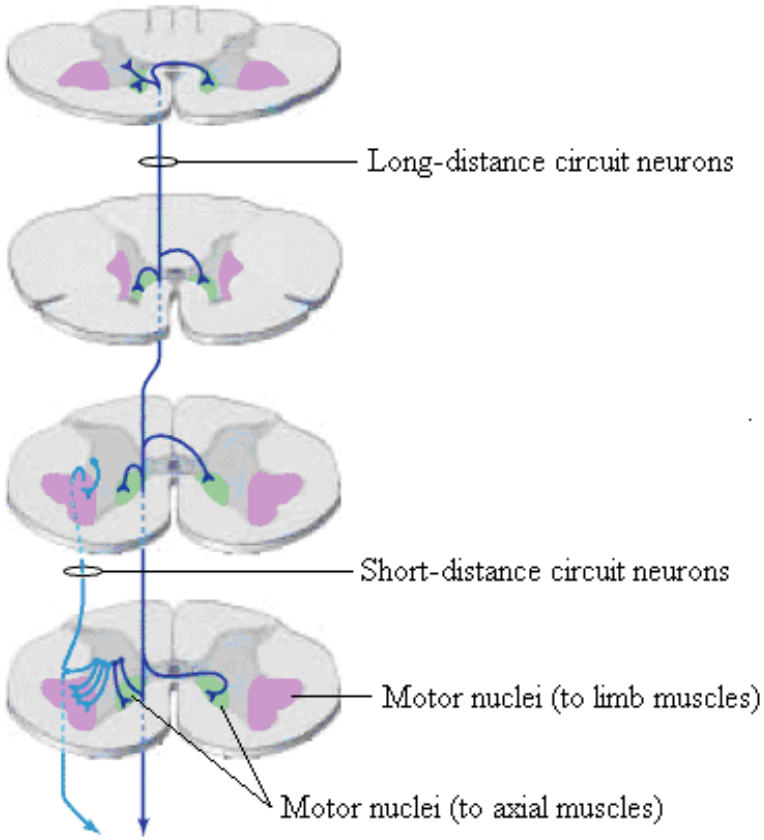

FIGURE 2. The motor nuclei of the axial and limb muscles are located somatotopically within the spinal cord. The intermediate zone of the spinal cord houses the spinal interneurons. (Purves et al. 2001, 370.)

2.1.2 Brainstem

Brainstem is a term used to describe the three lowest regions in the brain, which are, from inferior to superior, medulla, pons, and midbrain. Brainstem contains distinct nerve clusters, which are continuous with the spinal cord, and contribute to different sensory and motor systems in various ways. The medulla for instance controls neck muscles and is also involved in the maintenance of balance, pons relays information about movement and sensation from the cerebral cortex to the cerebellum, and midbrain functions as a link between different motor

system components, especially so between the cerebellum, the basal ganglia, and the cerebral hemispheres. (Kandel et al. 2000, 322; Shumway-Cook & Wollacott 2001, 52.)

2.1.3 Cerebellum

Cerebellum is a brain region that lies over the pons and has the greatest number of neurons of all the subdivisions of the brain, including cerebral hemispheres. Its internal structure is relatively simple and it projects to all of the motor structures of the brain, either directly or through relays. It receives somatosensory information from the spinal cord as well as motor information from the cerebral cortex. It also receives information from the vestibular organs of the ear. Because of its complex connections, cerebellum has various functions in motor control. It is an important feedback loop, making movement adaptation possible, and is therefore necessary for fast, accurate, and smooth movements. Cerebellum is also important in the maintenance of balance, and in coordinating head and eye movements. (Robinson 1995; Kandel et al. 2000, 322.) Recent studies have shown that cerebellum, together with the basal ganglia, also plays a role in higher cognitive functions, such as learning. It participates in the sequencing of the cognitive tasks and especially the timing of these tasks. (Doya 2000; Dreher & Grafman 2002.)

2.1.4 Diencephalon

Diencephalon is a brain region that has two major subdivisions, thalamus and hypothalamus. Thalamus occupies almost 80 % of the diencephalon; its most important function is to serve as a link in the transfer of sensory information from the periphery to the cerebral hemisphere regions that process sensory information. Thalamus is not purely a relay station since it also plays gating and modulatory role in relaying the information, in a sense thalamus determines whether the information reaches conscious awareness. Thalamus also integrates motor information from the basal ganglia and the cerebellum and transmits it to the motor cortex. Hypothalamus does not have a direct contribution to movement control, but it controls a variety of other bodily functions and serves an important role in the motivational system of the brain, thus, enabling movement. (Kandel et al. 2000, 322.)

2.1.5 Cerebral Hemispheres

Cerebral hemispheres are a part of brain that is considered to be responsible for the so called higher nervous activity, it is also considered as the highest level of motor control hierarchy (Shumway-Cook & Wollacott 2001, 52). Cerebral hemispheres include the cerebral cortex, the basal ganglia and three other subdivisions. All together cerebral hemispheres are involved with most of the higher neural activity including perceptual, motor, and cognitive functions. (Kandel et al. 2000, 322.)

Basal ganglia consist of five large subcortical nuclei; putamen, globus pallidus, caudate nucleus, subthalamic nucleus, and Substantia nigra (Figure 3). The basal ganglia do not receive direct inputs or send direct outputs to spinal cord, thus being a major centre in the complex extrapyramidal motor system. Instead of spinal cord it receives its input from most parts of the cerebral cortex and sends information via the thalamus mainly to motor cortex. In motor control the basal ganglia are mostly involved in the organization of automatic or sub-voluntary movements, but it also plays a role in error correction mechanisms. Basal ganglia, however, are not purely a motor centre as thought earlier; they participate in multiple neuronal pathways, thus, having also emotional, motivational, associative and cognitive functions. (Herrero et al. 2002.)

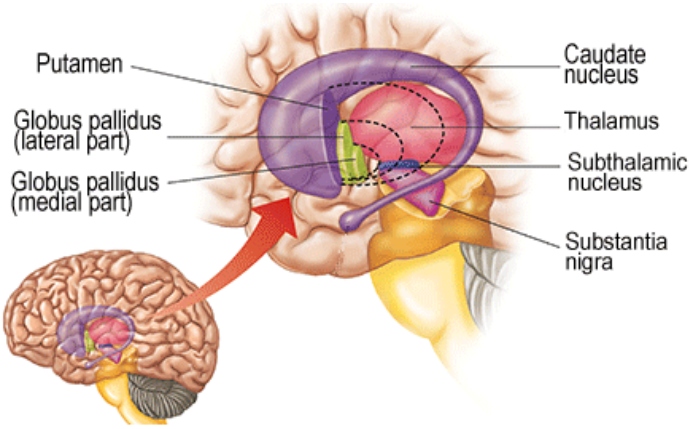

FIGURE 3. The five nuclei of basal ganglia and thalamus. (http://www.speakcapaigns.org/PD.php)

The term motor cortex has two different meanings. In a broader sense it is used to describe distinct cortical areas that control voluntary movement collectively (Figure 4). On the other hand it is used to describe only one of those areas, the primary motor cortex. (Wise 2004.) The motor cortex is located in the caudal part of the prefrontal cortex and it is histologically distinct because of its almost complete lack of granular cells, therefore, sometimes called the agranular frontal cortex. The cortical motor system is a complex mosaic of anatomically and functionally distinct areas. Together with their motor tasks, these areas also play a role in higher order functions, such as sensory-motor transformation and decision making. (Rizzolatti & Luppino 2001; Rizzolatti et al. 1998.)

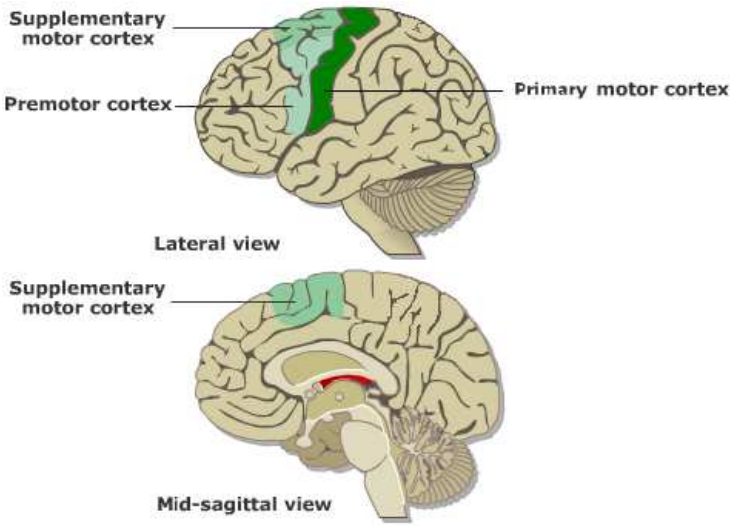

FIGURE 4. The cortical motor areas. (Get Body Smart 2009.)

The primary motor cortex (Figure 5) is a rather small part of the cerebral cortex, but its importance in the control of movement is unmatched. The primary motor cortex receives relatively direct inputs from most brain regions and spinal cord. It also sends outputs to most parts of the brain on top of which it has direct output to the spinal cord, thus, making it a major part of the pyramidal motor system. Some neurons of the primary motor cortex even have axons that terminate directly to the motor neurons in the spinal cord giving it the most direct possible access to muscles. (Wise 2004.) The primary motor cortex is thought to be the most important part in the control of voluntary movement. Its main function is to change the complex motor actions developed by the premotor areas into elementary movements. Because of its direct connections

to the muscles, it is also important in the fine control of movements, especially fine control of hand and digits. (Rizzolatti et al. 1998.)

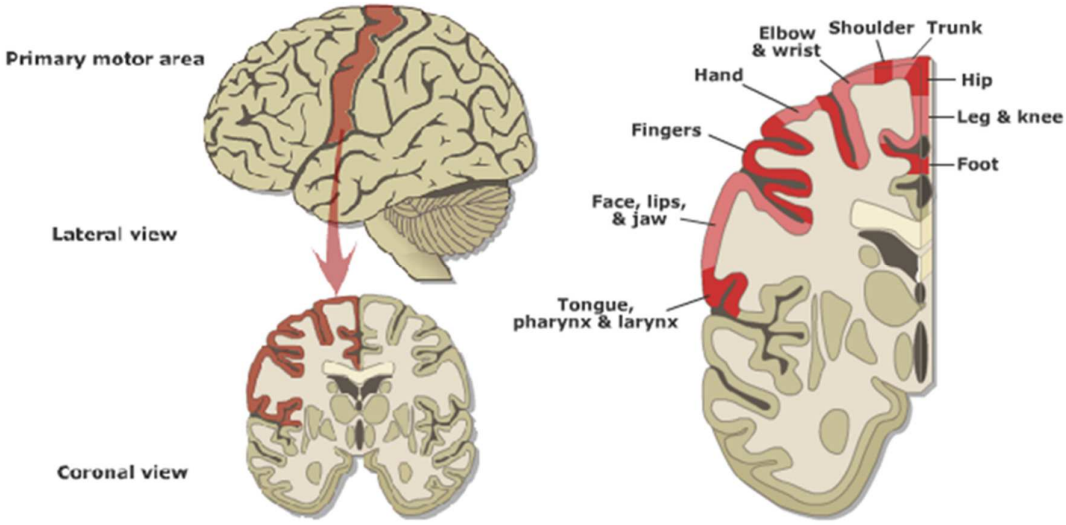

FIGURE 5. The primary motor area is the located in the precentral gyrus. Different parts of the body are arranged somatotopically on to the primary motor cortex. (Get Body Smart.com 2009)

In the broader sense the term motor cortex also includes the premotor areas. At least six spatially different premotor areas have been found in the frontal lobe of primates. Two of these, the ventral and the lateral premotor area, are in the lateral surface of the hemisphere. Remaining four, the supplementary motor area and the three cingulate motor areas, are on the medial wall of the hemisphere. Inputs to premotor areas are the same than for the primary motor cortex. The outputs of the premotor cortex, however, are different. Classically it was thought that premotor areas only had outputs to the primary motor cortex. Recently however, it has been shown that this is not the case, since the premotor areas can also influence motor output on the spinal level. It is believed that each of the premotor areas has a distinct role in motor control (Dum & Strick 2002). In the control of movement premotor areas are involved in identifying targets, choosing the course of action, and programming movements (Rizzolatti et al. 1998). The premotor areas, especially the supplementary and the pre-supplementary areas, also have a role in learning new motor tasks (Ashe et al. 2006).

2.2 Types of movement

The motor systems produce three types of movements; reflexive, rhythmic and voluntary. Reflexes are the simplest form of movement; they are involuntary coordinated patterns of muscle contraction and relaxation caused by peripheral stimuli. For the most part reflexes are integrated in the spinal cord but they can be modulated by input from the higher centres. Simplest of the reflexes is the monosynaptic stretch reflex. In stretch reflex the sensory neurons located in the muscle, called muscle spindles, are activated by a stretch to muscle. Axons of these neurons form excitatory synapses with motor neurons of the same muscles, so the activation of the muscle spindle by a stretch leads to the contraction of the muscle in question. Other reflexes include the withdrawal reflexes caused by cutaneous receptors and the postural reflexes, integrated in the brainstem according to the continuous flow of visual, vestibular, and proprioceptive information, that help us maintain posture during standing and locomotion. (Kandel et al. 2000, 654; Purves et al. 2001, 347.)

A slightly more complex form of movement is rhythmic movement. Rhythmic movements are used to generate a wide variety of behaviours in animals, including for example breathing, chewing, scratching, and locomotion. Rhythmic movements can be produced without higher control and without sensory input. Locomotor rhythms, such as walking and running, however, need to be modulated by sensory input to match them to the environment. Initiation and termination of the locomotor rhythms also requires higher control. (Marder & Calabrese 1996.) Rhythmic movements of the limbs are controlled by neural networks formed by the spinal interneurons called the central pattern generators. These neural networks are capable of producing alternate contraction and relaxation of muscles in a repetitive and rhythmic fashion. (Purves et al. 2001, 347.)

Automatic reflexes and rhythmic movements are relatively stereotyped actions that do not necessarily require higher control. The complex sequences of voluntary movements, however, are planned and controlled by the motor and pre-motor areas of the cerebral cortex. When compared to reflexes voluntary movements are different in many ways. First of all voluntary movements always have a desired outcome; a goal. This means that in a specific task the muscles used and

the joints rotated are selected according to the goal of that task. Secondly you can greatly improve, trough experience and learning, the efficiency of voluntary movements. Voluntary movements can also produce different responses to same stimulus and furthermore they can be generated internally without an external stimulus. (Kandel et al. 2000, 757.)

2.3 Motor coordination

Generally the word coordination refers to the optimal relationship among events (Frank & Earl 1990). The Stedman's medical dictionary (2002) defines coordination as "Harmonious functioning of muscles or groups of muscles in the execution of movements." In movement sciences work of Russian physiologist Nikolai Bernstein on coordination is often used as a starting point. Bernstein (1967) defined motor coordination as mastering the multiple degrees of freedom involved in a particular movement by reducing the independent variables to be controlled.

2.3.1 Coordination of muscles

There are over 250 skeletal muscles in the human body, each of which produces a distinct action at one or more joints. In principle, each of these muscles could be controlled individually by the central nervous system, making it possible to produce any combination of achievable forces. This, however, would lead to considerable neural redundancy. (Kandel et al. 2000, 687) The task of motor coordination is made even more complex because of the nonlinear properties of the muscle (Bernstein 1967). So instead, nervous system learns, through trial and error, which combination of muscles is best suited for a specific movement task. Differences in muscle architecture and fibre type distribution, makes it possible to influence the efficiency of performance and speed of force production, by varying the combination of muscles used. (Kandel et al. 2000, 687.)

There are many ways through which the CNS simplifies the task of motor coordination and many factors that influence it. Some of which are discussed in the following paragraphs. According to Prilutsky (2000) there are 244 degrees of freedom in the human body together with the even higher number of muscles there is an infinite number of possible ways to perform a motor task. Still a well learned task is coordinated very similarly by various individuals. This

has led to the hypothesis that The CNS has to use same control principles in various people. Main aim of the CNS seems to be to optimize the task according to one of three factors, which are metabolic energy expenditure, muscle fatigue, and the sense of perceived effort. Prilutsky (2000) has defined three rules of muscle coordination. These rules partially explain how the CNS chooses which muscles are activated and at which level. The first rule states that relatively more force is allocated to muscles that have a greater moment arm. According to the second rule a greater amount of force is allocated to the muscles that have a greater physiological cross-sectional area. The third rule highlights the synergistic action exhibited by the muscles. That is, agonistic muscles tend to be activated simultaneously, which leads in to a greater number of active muscles compared to the degrees of freedom.

If a muscle produces a moment in the same direction as the resultant joint motion it is called an agonist. If the moment produced by a muscle is opposite to the direction of the resultant joint motion then the muscle is acting as an antagonist. (Prilutsky 2000.) Simultaneous activation of agonist and antagonist muscles is called co-contraction. The co-contraction of agonist and antagonist pairs is one of the factors that need to be controlled in a coordinated task, because the level of activity of the antagonist affects the efficiency of the task, maximum torque produced, and stability of the joint. Increased antagonist activation is accompanied with a greater stability at the joint that the co-contracting muscles cross, whereas, a lower antagonist activity allows a greater net torque to be produced and requires less work done by the agonist to produce a certain submaximal torque level. (Ford et al. 2008.)

Muscles that are able to produce moments in the same direction around a joint are called synergistic muscles. In many cases it is not possible to produce a sufficient torque required by a task with a single muscle. Synergistically or co-functionally working muscles make it possible to produce greater joint moments and also allow for a greater time to exhaustion in tasks requiring prolonged submaximal muscle activity. (Zajac 2002.)

The word synergy itself means “to work together” and it is also used in muscle coordination with another meaning; to describe muscle synergies. D’Avella et al. (2003) have defined muscle synergies as coherent activations of a group of muscles in time or space. It has been hypothesized that the CNS simplifies the task of motor control by using muscle synergies to reduce the

degrees of freedom. According to the hypothesis there are a limited number of muscle synergies that are flexibly combined to produce different muscle activation patterns based on supraspinal and afferent signals. These synergies are thought to be, at least partly, innate but have also been shown to adapt over long periods of time, which explains the variations found in the synergy patterns and the number of synergies between individuals. (Ting & McKay 2007, D'Avella & Bizzi 2005.)

Differences between one and two joint muscles also have an important role in the coordination. One-joint muscles are quite simple; they produce moments in a single joint and their activation is greatest when they work as agonists. Two joint muscles, however, are more complex because they produce moments in two joints. Their activation varies depending on the activity they have on both joints. The activity is at its greatest if a muscle acts as an agonist at both joints and the lowest if it acts as an antagonist at both joints, if a muscle acts as an agonist at one joint and as an antagonist at the other the activity is intermediate. (Prilutsky 2000.) The synergistic muscle action of one- and two-joint muscles is also important because it allows the transfer of energy between segments. (Zajac 2002.)

It has been shown also that individual muscles are more complex than traditionally thought. Segal et al. (1991) suggested that instead of simply consisting of fibres attaching to the sites of origin and insertion; muscles might have unique sub-compartments, called partitions, which differ from each other in pennation angle, direction of pull, points of origin and attachment, and fibre type composition. Each of the compartments within a muscle may have functional or task-oriented roles and unique physiological attributes. Therefore, during a motor task, the CNS can influence the efficacy, the rate of force production, and the direction of the overall force, through the control of individual partitions instead of whole muscles. (English et al. 1993.)

Afferent information from different sensory organs is also of great importance in motor coordination. In order for a motor task to be purposeful it needs to take into account the environment in which the individual is operating in. Motor programs often need to be adjusted to meet unexpected perturbations or changes happening in the external environment. Visual input is often thought to be the most important source of sensory information in relation to adapting to the external environment. On many occasions however, proprioceptive information is the fastest

and most accurate source of information and it is therefore considered essential in the control of movement. Afferent information is also important during planning of movements. It is used to identify variables of the environment, such as slippery or uneven surfaces, that need to be taken into account in the planning of the movement. Visual information is also used to produce a model of the environment in which the movement is going to be executed. (Riemann & Lephart 2002.)

Proprioception also has another important role; in accommodating the musculoskeletal mechanics. Because of the mechanical properties of muscles, the force that a muscle produces in response to a certain motor command is not constant. Properties such as muscle length and its rate of change affect the muscles force production. Proprioception provides this information to the CNS, thus, making it possible for the CNS to accurately control the muscle force. The information provided by the proprioceptors is vital for example when the muscle undergoes unexpected changes in length. Proprioceptors also provide the feedback information needed in the control of the movement of several joints. In a linked system such as human body, movements of one body segment influence all the other segments. Information from the proprioceptors makes it possible for the system to interpret these interactions and to coordinate the activity of the individual segments. (Riemann & Lephart 2002.)

3 ANATOMY AND FUNCTION OF THE LOWER LEG

3.1 Anatomy of the ankle joint

Ankle joint (Figure 6.) is a synovial hinge joint, which, medially and proximally consists of a bony fit between the distal end of tibia and its medial malleolus and the talus; and laterally between the lateral malleolus of the fibula and the talus. The shape of the trochlea of the talus is anteroposteriorly a convex and from the medial to the lateral side a convex-concave-convex. These surfaces contact with the reciprocally shaped areas of the distal end of the tibia. The relatively flat lateral side of the talus articulates with the likewise flat articular surface of the distal fibula. The tibia and fibula and their malleoli enclose the talus and form a sort of a clasp in which the talus rolls. The width of the talus is greater anteriorly than posteriorly the same difference can be found in the width between the malleoli. This results in a snug fit between the trochlea and malleoli. The stability of the ankle joint is further helped by the distal tibiofibular joint, which is formed by the concave distal tibia and convex distal fibula. (Riegger 1988.)

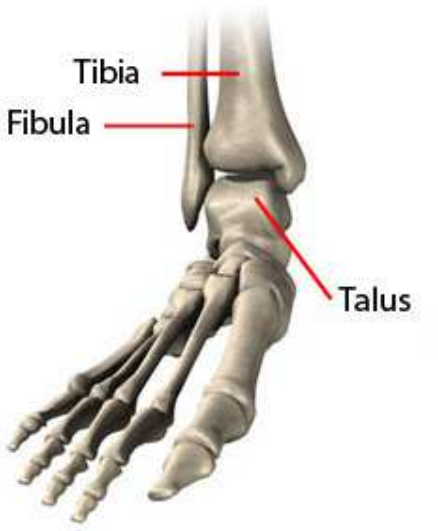

FIGURE 6. The ankle joint. (www.footlogics.com 2016)

The capsule of the ankle joint is attached to the joint surfaces of the tibia, fibula, and talus. Anteroposteriorly the capsule is slack, thus, allowing the desired movement. The joint capsule is reinforced by several ligaments. Largest of these is the deltoid ligament on the medial side.

It consists of three fasciae in two layers. The superficial layer covers the deeper layer completely. Its tibionavicular part is inserted into the navicular bone and the tibiocalcaneal part to the calcaneal bone. The deeper layer consists of tibiotalar part, which, can be divided into anterior and posterior fibres that insert into the talus. The lateral side has three smaller ligaments that include; the anterior and posterior talofibular ligaments, between the fibula and talus, and the calcaneofibular ligament between the fibula and talus. Also the two ligaments, anterior and posterior tibiofibular ligament, between the tibia and fibula add to stability of the joint. (Riegger 1988; Calais-Germain 2007.)

The ankle joint allows both dorsiflexion and plantar flexion of the foot. The axis of movement starts just below the medial malleolus and runs through the thickest part of the lateral malleolus. The range of movement in the joint is about 70 degrees between maximal dorsiflexion and plantar flexion. (Kahle et al. 1992, 218.)

3.2 Anatomy of the plantar flexor muscles

The plantar flexor muscles are located in the posterior compartment of the shank of the foot and can be divided into two groups. The superficial group consist of the soleus and gastrocnemius muscles, commonly referred to also as the triceps surae muscle, and the plantaris muscle. The deep muscle group consists of the tibialis posterior, flexor hallucis longus, and flexor digitorum longus muscles. The two groups are separated from each other by the deep transverse fascia of the leg. Also the two muscles of the lateral compartment, peronneus longus and peronneus brevis, act as plantar flexors (Riegger 1988.)

3.2.1 Superficial muscles

The parts of the triceps surae, the gastrocnemius with its two heads and the Soleus, originate from both sides of the knee joint and insert with a large common terminal tendon, called the tendo calcaneus or Achilles tendon, into the middle area of the posterior calcaneus. All the parts of the triceps surae muscle are innervated by the tibial nerve (S1-S2). (Riegger 1988) The triceps surae is the strongest plantar flexor, it can lift the weight of the whole body during standing and walking. The full activity of the muscle is only possible when the knee is fully extended,

because if the knee is bent is gastrocnemius already shortened. Because the origin of the gastrocnemius is on the femur, it also plays an important role in walking because it can both lift the heel and flex the knee. (Kahle et al. 1992, 258.)

The gastrocnemius (Figure 7) is a biarticular muscle that crosses both the knee and ankle joints. It arises from two heads on the posterior side of the femoral condyles and with some fibres from the capsule of the knee joint. The two heads of the Gastrocnemius are the lateral gastrocnemius and the medial gastrocnemius (Riegger 1988). Of the two parts the medial gastrocnemius is slightly larger. It is a unipennate muscle that originates from the medial femoral condyle. The fibres run longitudinally and insert onto the tendo calcaneus. The oval shape of the muscle means that the medial and lateral fibres curve in order to insert into the tendon, therefore, the muscle might sometimes appear bipennate. (Wolf & Kim 1997; Riegger 1988.) The medial gastrocnemius usually has a single primary nerve branch that on average separates from the tibial nerve approximately 0.8 cm below the intercondylar line, in some cases though the branch was located above the intercondylar line (Kim et al. 2002). The primary nerve usually divides into two secondary branches. The short secondary branch innervates the proximal fibres and the long secondary branch innervates the distal fibres (Wolf & Kim 1997). The motor point of the muscle is located 11.6 % of the lower leg length below the intercondylar line (Kim et al. 2002).

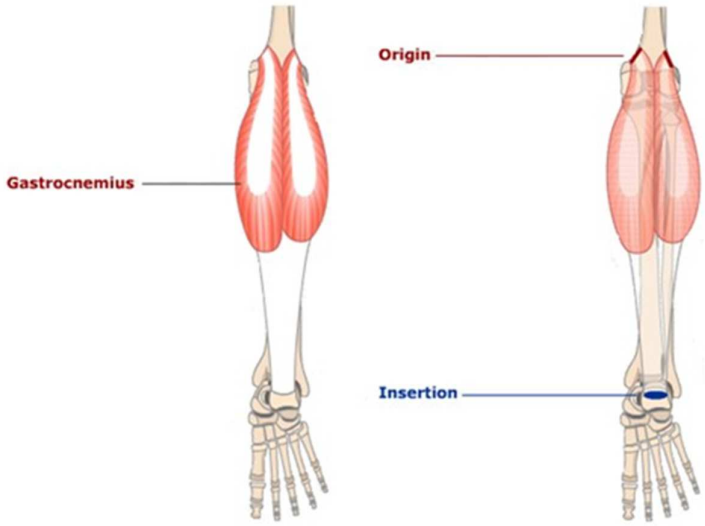

FIGURE 7. The two heads of the Gastrocnemius muscle and their attachments. (Get Body Smart 2009.)

The lateral gastrocnemius originates from the lateral femoral condyle with two tendons; a large superficial tendon and a small deeply situated tendon. Unlike the medial gastrocnemius, it can be divided architecturally into three parts. The first part has longitudinal fibres that arise from the deep surface of the superficial tendon and attach to the superficial surface of the main portion of the tendo calcaneus. The second part arises from the superficial surface of the superficial tendon. Its fibres run obliquely and insert onto the superficial surface of the crus of the tendo calcaneus. The fibres of the third part run longitudinally originating from the superficial surface of the deep tendon and insert onto the deep surface of the crus. The three architectural parts of the lateral gastrocnemius muscle are usually innervated by a single primary motor nerve branch that divides into two main trunks; lateral and medial trunks (Segal et al. 1991). Kim et al. 2002 found that in 91.6 % of the cases there was a single primary motor nerve that separated from the tibial nerve approximately 1.4 cm below the intercondylar line. They also found that in 80.0 % of the cases, there was a single motor point in the muscle, which is situated on the lateral side of the calf approximately 10.7 % of the lower leg length below the intercondylar line.

The soleus (Figure 8) originates from the head and upper third of the dorsal surface of the fibula; and from the line of the soleus in the tibia (Riegger 1988). It is large flat muscle that can be divided into two parts; the anterior and the posterior part. The anterior soleus is the deeper of the two parts. It is a bipennate muscle that is separated from the posterior soleus by an aponeurosis. The unipennate posterior soleus lies between the anterior soleus and the gastrocnemius. The fibre bundle lengths in relaxed muscle for anterior and posterior parts are 26.9 mm and 29.7 mm, and the pennation angles, measured between the fascicle and the median septum in the anterior part and between the fascicle and the anterior aponeurosis for the posterior part, are16.5 and 23.7 degrees respectively. (Martin et al. 2001.) The soleus muscle has a single motor nerve branch that separates from the main tibial nerve 3.3 cm below the intercondylar line. The motor point of the muscle is situated at 18.2 % of the lower leg length below the intercondylar line. (Kim et al. 2002.)

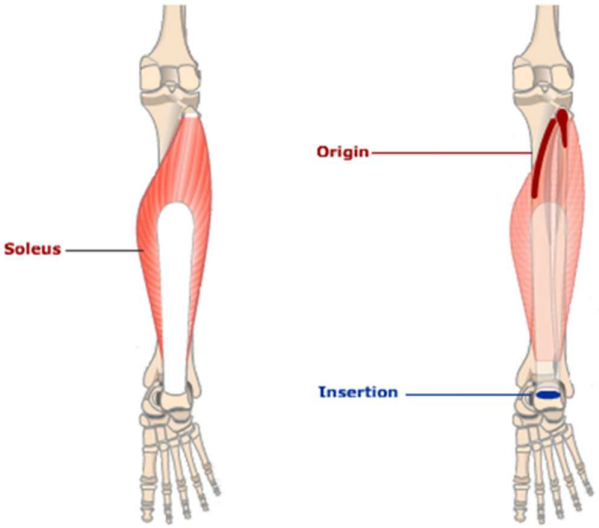

FIGURE 8. The Soleus muscle and its attachments. (Get Body Smart 2009)

3.2.2 Deep muscles

The deep layer of muscles in the posterior compartment of the leg is composed of the popliteus, tibialis posterior, flexor digitorum longus, and flexor hallucis longus muscles (Figure 9). Except for the popliteus the muscles arise from the posterior surfaces of the tibia and fibula, from the interosseous membrane, and posterior peronneal intermuscular septum. Like the muscles of the superficial layer the muscles are innervated by the tibial nerve. (Riegger 1988.)

The flexor hallucis longus originates from the distal two thirds of the posterior surface of the fibula, from the interosseous membrane, and the posterior crural intermuscular septum. The flexor hallucis longus is a relatively thick muscle that extends rather low down and then transforms into its tendon. The tendon attaches to the terminal phalanx of the hallux. The main function of the flexor hallucis longus is to plantar flex the hallux and the ankle. It also abducts and inverts the foot. Flexor hallucis longus is a strong push off muscle that is very important for example during walking and running. (Kahle et al. 1992, 260.)

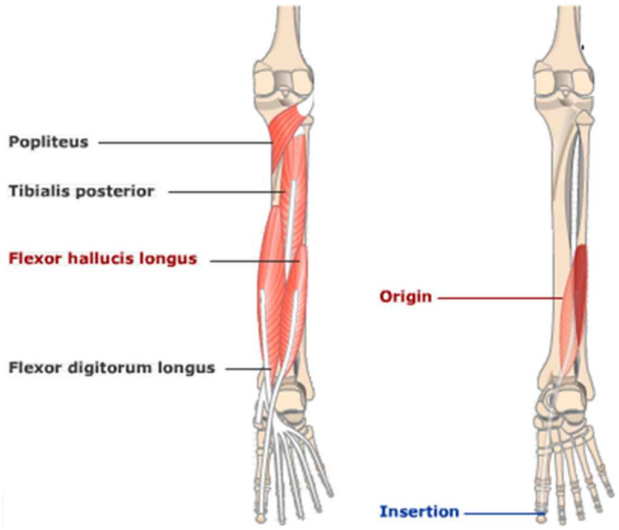

FIGURE 9. The deep muscles of the posterior compartment and the attachments for the Flexor hallucis longus muscle. (Get Body Smart 2009.)

3.3 Function of the plantar flexors

As mentioned above the superficial triceps surae, consisting of the gastrocnemius and the soleus, is the most important plantar flexing muscles. The cross-sectional area of these muscles is far larger than the cross-sectional area of the deeper muscles; therefore, they produce majority of the force in plantar flexion tasks. The deeper muscles, flexor hallucis longus, flexor digitorum longus, and tibialis posterior, together with the lateral compartment peronneus muscles also produce some of the force in plantar flexion tasks, although it is not their primary function. (Finni et al. 2006.)

There has not been a lot of research done on what are the contributions of the individual muscles in plantar flexion tasks. Gregor et al. (1991) used a buckle-type in vivo force transducer attached to the Achilles tendon to measure the force produced by the triceps surae during cycling. Using the moment arms they calculated the force produced by the triceps surae and compared that to the measured plantar flexion force. According to their measurement the triceps surae produced about 65 % of the plantar flexion torque. Zandwijk et al. (1998) estimated the contribution of the triceps surae to be about 85 %. They based their estimation on the physiological cross-sectional areas and moment arm lengths of the plantar flexor muscles.

It has been shown, however, that different people have different coordination strategies in plantar flexion tasks. Some people mostly use the triceps surae muscles to produce the plantar flexion torque, whereas, others show significant synergistic action from the deeper muscles as well as the peronneus muscles. These differences in the activation strategies might also be affected by the mode of exercise, by fatigue, and by the level of force required in a task. (Finni et al. 2000, Finni et al. 2006, Tamaki et al. 1998). Finni et al. (2006) used cine phase-contrast magnetic resonance imaging (PC-MRI) to measure muscle velocities of Achilles tendon rupture patients that had undergone a surgical repair and healthy controls during plantar flexion tasks. In their study they showed that deeper muscles contribute to the force production in a plantar flexion task. This was most evident when comparing the injured subjects to the healthy ones, but they also found high variability in the coordination between the healthy subjects. Masood et al. (2014) also found significant variability between individuals when they measured EMG and glucose uptake to measure muscle activity.

4 MEASUREMENT OF MUSCLE ACTIVITY

4.1 Electromyography

Electromyography (EMG) is a method of studying the electrical activity of the muscles. During a muscle contraction the electrical potential of a muscle fibre changes from negative to positive and back to negative, these currents can be recorded with electrodes to provide EMG data. (Enoka 2008, 197; Robertson et al. 2004, 163-165.)

In order for a muscle to contract the central nervous system activates a motoneuron. Electrical impulse is carried down by the motoneuron and once it reaches a motor endplate, a specialized synapse between a motoneuron and a muscle fibre, it results in a muscle fibre action potential. At its resting state the inside of a muscle fibre has an electrical potential of -90 mV. Due to an end plate potential the muscle fibre membrane becomes more permeable to Na^+ and thus more Na^+ flows inside the fibre reversing its polarity to positive, resulting in a membrane potential of about 30 mV. This change in polarity causes the membrane to then become more permeable to K^+, which starts to flow out of the cell and repolarizes it back to its resting state. The muscle fibre action potential is generated at a small section close to the nerve-muscle synapse. The action potential then propagates along the muscle fibre and ensures that the whole fibre is activated resulting in the contraction of the muscle fibre. (Enoka 2008, 197; Robertson et al. 2004, 163-165.)

EMG can be measured with a variety of different electrodes types, either noninvasively from the surface of the skin or invasively from inside the muscle itself. The number of the electrodes used can also vary from a monopolar setup to multielectrode arrays. The choice of the electrode type and number of electrodes depends on the motor task and the data needed. (Robertson et al. 2014, 182-185.)

Surface EMG can provide data on the activity level of an entire muscle. A monopolar setup, where a single electrode is placed over the muscle and another over a bony prominence or another electrically neutral site, is mostly suited for static movement tasks. By far the more common method is to do bipolar measurements where two electrodes are placed over the skin

and a ground electrode on an electrically neutral site. Compared to monopolar measurements the bipolar setup is better suited for all movement types and not limited to just isometric contractions. Because bipolar electrodes measure the difference between the two electrodes it is therefore also less sensitive to outside signal interference that results from electronic devices and power lines etc. More invasive methods use fine wire and needle electrodes that are inserted in to the muscle. They can provide a more detailed picture of the muscle contraction by making it possible to record EMG from deeper and smaller muscles and even the activity of a single motor unit. (Robertson et al. 2014, 182-185.)

4.2 Magnetic resonance imaging

Some ultrafast kinematic MRI procedures can be used dynamically to measure the overall deformation of skeletal muscle during muscle activity. In these measurements a series of images is taken during a certain time frame. These images are then analysed with the use of anatomical landmarks to distinguish between different muscle groups. However with these methods it's not possible to measure the contraction-induced local displacements at any location within the muscle. Local displacement information is vital to the understanding of basic muscle biomechanics and local contractile failure. Local displacement data can also be used to quantify the strain distribution of the muscle which is important in order to understand the muscle function. Two MRI methods used to track local displacement of muscle tissue due to motion are tagging and phase-contrast sequences. (Prompers et al. 2006.)

Phase contrast magnetic resonance imaging (PC MRI) allows quantitative measurement of three-dimensional velocity over an entire imaging plane (Asakawa et al. 2003). In a phase contrast MRI protons of the tissue are coded for velocity so that contrast, of the pixels in the image represents the velocity of the tissue in question (Komi 2003 s.147).

PC MRI can only be used to calculate the trajectories of the points within the tissue from which the motion of the tissue can then be derived by integrating the velocities. However velocity measurements at a specific image location as a function of time usually corresponds different material points. (Prompers et al. 2006.) In order to track specific material points a combination

of PC MRI and cine MRI needs to be used. Cine phase contrast MRI makes it possible to quantitatively measure both tissue anatomy and velocity in all three directions during dynamic tasks. (Asakava et al. 2003.)

In cine phase contrast MRI image data is collected during multiple cycles of periodic motion. The data is then sorted in to the desired number of time frames to produce two sets of images from different temporal phases during the muscle contraction. One of the sets contains the velocity information (phase contrast images) and the other the anatomical information (magnitude images) (Figure 10). The anatomical images are used to define regions of interests (ROIs) within the muscle, usually rectangular areas, which are then superimposed over the phase contrast images from which the velocities can be ascertained for all the phases. (Asakava et al. 2003. Finni et al. 2006.)

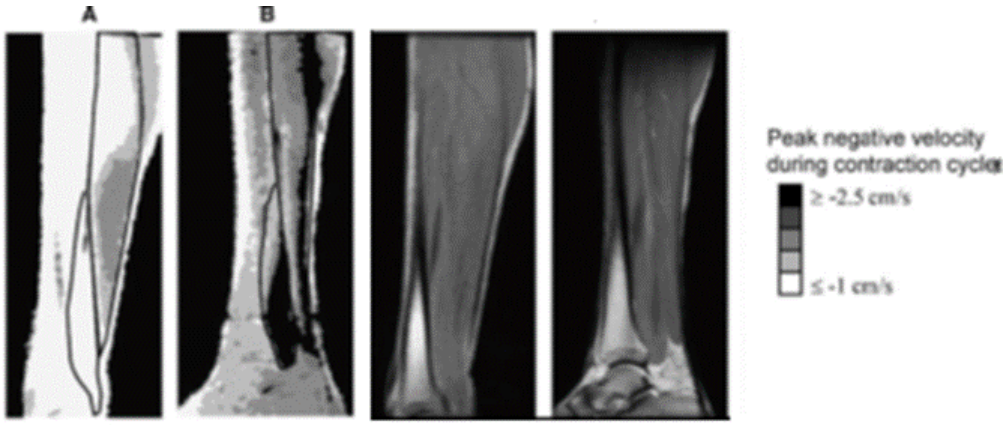

FIGURE 10. The top two pictures show the velocity pattern during passive ankle joint movement (A) and during voluntary isometric contraction (B) the lower pictures are the anatomic magnitude images that were used to identify the ROIs (Modified from Finni et al. 2006.)

Motion data collected from the phase contrast images can be used to calculate the local strain pixel-by-pixel. It can also be used to directly measure the strain rate. However there are several practical challenges concerning the acquisition of cine PC data. In order to get the data required to produce all the temporal phases a number of motion cycles needs to be imaged, usually 60-120. This means that the loads that can be used are very low and it also makes it difficult to use the cine PC MRI to measure the muscle mechanics of injured and unhealthy people. The joint motion also needs to be highly repeatable. In addition to repeatable motion the selection of the

imaging plane is important because large amounts of out-of-plane tissue motion can become a problem when calculating the tissue displacement from the velocity data. (Asakava et al. 2003.)

In the future many of the problems concerning cine PC MRI can be avoided with the use of real-time MRI techniques. Real-time PC MRI has the advantage of measuring tissue motion in real time and therefore there is no need for the cyclic actions required in the cine PC MRI. The scan time is also reduced significantly. (Asakava et al. 2003.)

5 PURPOSE OF THE STUDY

In this study the activation of three different plantar flexor muscles, gastrocnemius, soleus, and flexor hallucis longus, was measured during low torque plantar flexion tasks. Two different methods, surface electromyography and cine phase-contrast magnetic resonance imaging, were used to assess the activity of the muscles. The purpose of the study was to see whether there are differences in the way individuals use their plantar flexor muscles during plantar flexion tasks i.e. do some people produce a greater relative amount of the plantar flexion torque with the deeper muscles compared to other people. The second objective was to see whether the two measurement methods are comparable, in essence do the results correlate with each other and are the results otherwise similar.

5.1 Research questions

1. Does the relative level of activation between deep and superficial plantar flexor vary among individuals?
2. Does the exerted torque level have an effect on the relative level of activation?
3. Does the relative level of activation change with different movement tasks?
4. Do the results of the two different methods (PC MRI and EMG) correlate with each other?

5.2 Research hypothesis

1. There are statistically significant differences in the relative activation levels of the plantar flexor muscles between individuals.
2. The exerted torque level affects the relative levels of activation.
3. The relative activation levels are different in different tasks.
4. The two methods provide comparable results that correlate with each other.

6 METHODS

6.1 Study subjects

A total of fifteen subjects took part in the measurements. For five of the 15 subjects taking part to the study the MRI data was too corrupted for analysis and therefore they were not included in the analysis. The ten subjects that were subjected to closer examination included seven men [mean 26 (SD 3) years, 76 (11) kg, 176 (5) cm] and three women [mean 27 (SD 3) years, 59 (9) kg, 167 (2) cm]. All subjects were physically active. On average they did endurance training more than once a week and strength training a few times a month. The subjects were carefully informed about the protocol of the study. Thereafter, the subjects signed a written informed consent to participate in the study, which had been approved by the ethics committee of the University of Jyväskylä, Finland.

6.2 Measurements

Subjects took part in two exercise sessions where the activity of the calf muscles was measured. First exercise session took place in a biomechanics laboratory where surface electromyography (EMG) was used to measure the muscle activity. Second set of exercises was done inside an MRI scanner using phase-contrast magnetic resonance imaging (PC-MRI) to measure the speed of the muscle tissue during the contraction cycle. For the measurements the subjects were lying supine and their right foot was fixed on a foot plate of a special force measurement apparatus (Figure 11) constructed at the University of Jyväskylä. The ankle was fixed in an angle of 90 degrees and the legs were secured to the table from the thigh in order to minimize the use of muscles above the knee. The subjects performed plantar flexion movements by pushing against the foot plate of the apparatus. The foot plate of the apparatus could be fixed in place to allow isometric contractions or allowed to move so that concentric contractions could be performed, in which case a number of springs were used to produce various loads. Two vertical light bars (Figure 12), consisting of ten optical cables, were used to give feedback to the subject so they could maintain the target force and the desired rhythm of contractions.

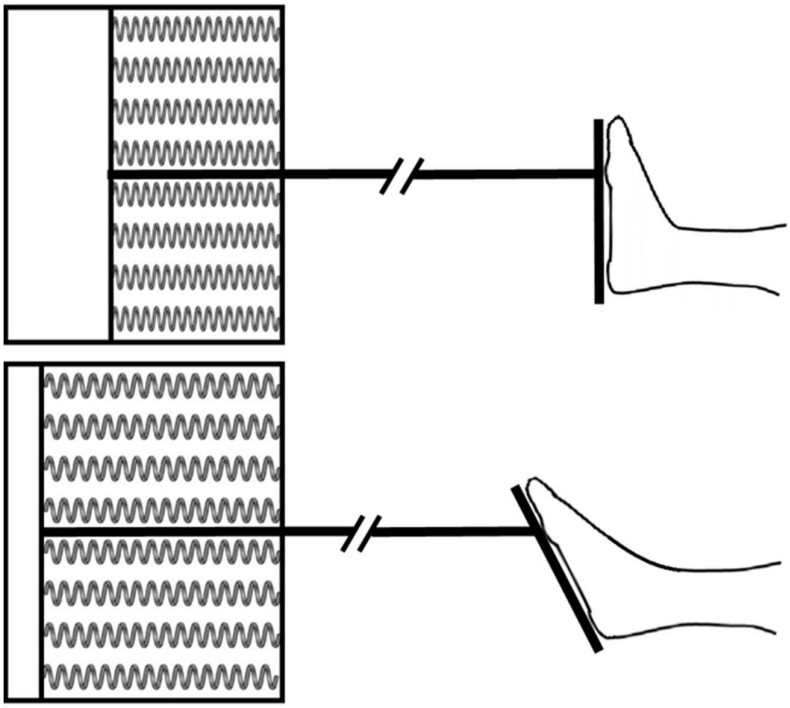

FIGURE 11. Illustration of the force measurement apparatus. Ankle at 90 degrees at rest and in isometric tasks. In concentric task the load could be adjusted by changing the number of springs.

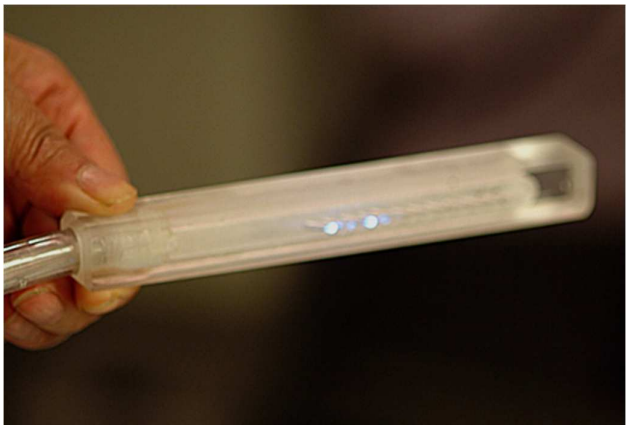

FIGURE 12. One of the optical cable light bars used to visualize the torque level and rhythm.

In the laboratory measurements (Figure 13) the subjects first performed three maximal voluntary contractions (MVC), best of which was used to calculate the three force levels to be used during the measurements. Subjects then performed two to three sets of static isometric and cyclic isometric plantar flexion contractions at 10 % and 30 % of the MVC. They also performed

Two to three sets of cyclic concentric contractions at 10% and 30%. For few of the male subjects the maximum number of eight springs only corresponded to about 20 % of their MVC. Both isometric and concentric cyclic contractions were made at a rate of 40 cycles/min for 90 seconds.

FIGURE 13. Measurement setup for the laboratory measurements. The brown plywood box is the force measurement apparatus depicted in figure 11.

6.2.1 EMG measurements

In the laboratory measurements surface EMG was measured from the medial gastrocnemius, peronneus, flexor hallucis longus, and tibialis anterior muscles. Two disposable Ag/AgCl electrodes, surface area of 13.2 mm^2 (Blue Sensor M, Ambu Incorporated, Denmark), were used with an inter electrode distance of 20-mm to produce a bipolar electrode. EMG electrodes were placed according to the SENIAM guidelines, except for the flexor hallucis longus, for which the electrode was placed posterior to the medial malleolus. A ground electrode was placed on the lateral epicondyle at the knee. The skin was shaved, abraded and cleansed before attaching the electrodes. The EMG data was collected to a computer using the CED Power 1401 AD converter (Cambridge electronic design limited, UK.) and the Signal v. 2.0 program (Cambridge electronic design limited, UK.). Sampling frequency of 2 kHz was used and the signal was preamplified and bandpass filtered 20 Hz to 400 Hz. For further analysis a root mean square

(RMS) of EMG amplitude was calculated. A window of 200 ms preceding the maximum torque was used for the cyclic measurements. For the MVC the window was 1000 ms. From 500 ms before to 500 ms after the maximum torque.

6.2.2 PC-MRI measurements

The second set of measurements was done in using an MRI scanner (1.5-T GE Signa CV/i scanner, GE Medical Systems, Waukesha, WI) (Figure 14). A body coil was used to gather the anatomical and functional (muscle velocity) information. The protocol was similar to the one used in the laboratory. The subjects made 2 series of isometric contractions at the loads of 10 and 30 % of MVC and two series of concentric contractions against two different spring loads corresponding to about 10 and 30 % of the isometric MVC. The series consisted of about 70 contractions made at the rate of 40 cycles/min. The MRI data acquisition was triggered from the force signal in order to assure that the acquisition was started from the same movement phase in each of the contractions.

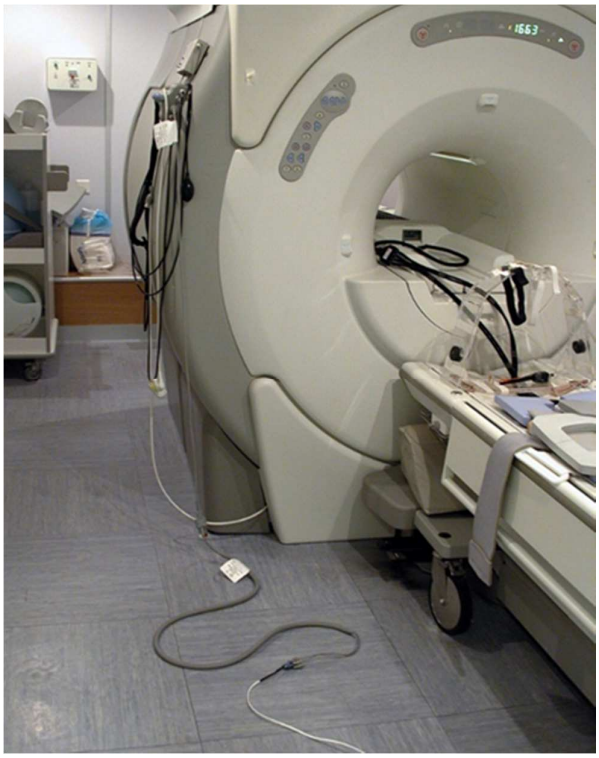

FIGURE 14. GE medical systems MRI scanner used in the study.

Velocity of the tissue movement during contraction cycles was acquired using velocity-encoded phase-contrast MRI (VE-PC MRI). This method produced two sets of 256 by 256 pixel images, each consisting of 20 temporal phases of the movement cycle, 75 ms apart. One set of images contained velocity information (phase-contrast images) and the other anatomic information (magnitude images). Sagittal images showing the soleus, medial gastrocnemius, and flexor hallucis longus muscles, was acquired in the VE-PC scans. Rectangular regions of interest (ROI) from the distal parts of the three muscles were defined on the anatomical images (Figure 15). The ROIs were then superimposed to the phase-contrast images.

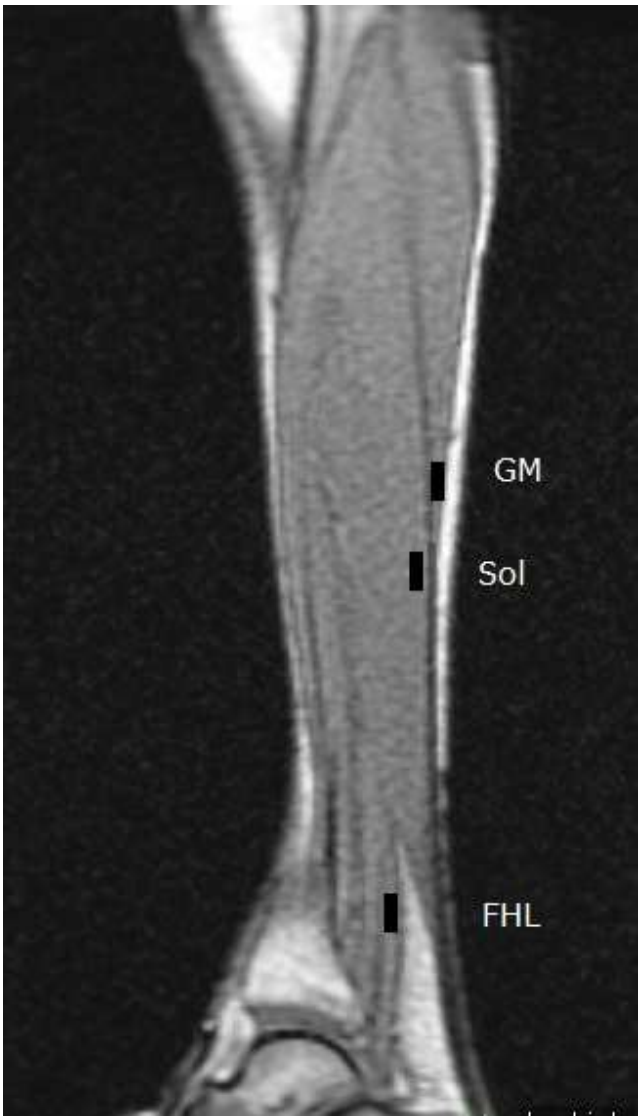

FIGURE 15. The location of the regions of interest for gastrocnemius medialis (GM), soleus (Sol), and flexor hallucis longus (FHL).

The average velocities of muscle tissue within the ROI was quantified for each of the 20 pictures in the series. The velocities represent the activity of the muscle during the contraction cycle. Negative velocities occur when the muscle is contracting and positive during the relaxation phase. The velocity is zero during rest and at peak torque. Ratios for the peak negative average velocities between soleus and flexor hallucis longus, and gastrocnemius and flexor hallucis longus were calculated. These ratios represent the relative contribution of the muscles towards the total torque. Low values indicate a greater contribution from the deeper plantar flexor. Higher values meaning that the deeper plantar flexor had little to no contribution.

6.3 Statistics

Shapiro-Wilk test was used to determine whether the data is normally distributed. Velocity data from the PC MRI measurements was normally distributed and a paired sample t-test was used. Some of the variables of the EMG measurements were not normally distributed, therefore, a nonparametric Wilcoxon signed rank test was used to test the EMG data. The pooled datasets used for the correlations were not normally distributed, therefore a nonparametric Spearman's correlation was used.

7 RESULTS

7.1 EMG measurements

Due to corrupted data in the MRI measurements 5 subjects were excluded from further analysis also in the EMG measurements. Table 1. lists the RMS EMG for the ten subjects, as well as, averages and standard deviation in the four different tasks.

TABLE 1. RMS EMG of gastrocnemius medialis (GM), soleus (Sol), and flexor hallucis longus (FHL) in isometric (Iso) and concentric (Con) tasks at the two different torque levels.

	GM				Sol				FHL			
	Iso		Con		Iso		Con		Iso		Con	
Subject	10 %	30 %	10 %	30 %	10 %	30 %	10 %	30 %	10 %	30 %	10 %	30 %
1	0,040	0,080	0,124	0,086	0,035	0,096	0,172	0,136	0,002	0,080	0,106	0,077
2	0,061	0,124	0,051	0,123	0,016	0,026	0,059	0,117	0,007	0,007	0,009	0,097
3	0,024	0,077	0,034	0,040	0,124	0,210	0,171	0,141	0,080	0,093	0,058	0,087
4	0,098	0,254	0,141		0,078	0,157	0,084		0,070	0,025	0,005	
6	0,020	0,040	0,013	0,019	0,028	0,027	0,096	0,069	0,013	0,009	0,018	0,018
7	0,028	0,200	0,095	0,099	0,018	0,074	0,034	0,044	0,017	0,038	0,018	0,036
8	0,053	0,013	0,055		0,032	0,064	0,144		0,030	0,064	0,174	
10	0,029	0,217	0,088	0,146	0,036	0,097	0,084	0,091	0,048	0,159	0,096	0,074
12	0,115	0,162	0,181	0,148	0,018	0,060	0,034	0,043	0,014	0,037	0,108	0,146
15	0,041	0,037	0,026	0,045	0,039	0,116	0,089	0,117	0,020	0,027	0,014	0,016
Average	0,051	0,120	0,081	0,088	0,042	0,093	0,097	0,095	0,030	0,054	0,061	0,069
SD	0,031	0,080	0,052	0,046	0,032	0,054	0,048	0,037	0,026	0,044	0,055	0,041

As expected EMG showed a trend of higher EMG activity at higher load, the difference, however, was only statistically significant in isometric task for GM ($p<0.05$) and for Sol ($p<0.01$). The comparison between concentric and isometric tasks had also similar differences and was statistically significant at the 10% torque level For GM ($p<0.05$), and Sol ($p<0.01$). At 30% torque level no statistically significant differences were found.

7.2 PC-MRI measurements

During the contraction phase of the task, when the tissue moves in the proximal direction, the velocities are negative. For all subjects the peak mean negative velocities were found when the torque was rising. The peak mean negative velocities for all the subjects as well as the average and standard deviation are shown in table 2.

TABLE 2. The peak mean negative velocities (mm/s) of gastrocnemius medialis (GM), soleus (Sol), and flexor hallucis longus (FHL) in isometric (Iso) and concentric (Con) tasks at the two different torque levels.

	GM				Sol				FHL			
	Iso		Con		Iso		Con		Iso		Con	
Subject	10 %	30 %	10 %	30 %	10 %	30 %	10 %	30 %	10 %	30 %	10 %	30 %
1	-33,4	-66,3	-64,2	-63,8	-26,8	-64,9	-41,1	-52,9	-23,4	-35,6	-54,3	-69,5
2	-20,9	-38,8	-38,2	-75,8	-23,5	-40,7	-48,0	-96,3	-11,2	-18,4	-15,5	-40,2
3	-32,0	-80,6	-45,6		-22,9	-62,5	-25,9		-15,8	-61,3	-18,9	
4	-29,5		-52,4	-58,3	-29,5		-36,3	-45,0	-21,5		-24,0	-21,3
6	-8,6	-33,5	-30,9	-29,3	-8,2	-28,1	-21,8	-19,1	-13,5	-23,7	-15,2	-22,0
7	-44,3	-37,9	-45,8		-36,2	-29,3	-30,4		-26,5	-30,5	-23,2	
8					-28,9	-50,5	-28,9	-34,7	-26,6	-41,5	-25,6	-36,8
10	-28,0	-46,2	-41,3		-20,1	-33,5	-41,2		-23,6	-44,9	-28,2	
12	-52,7	-94,7	-84,4	-102,1	-37,0	-75,8	-72,2	-98,0	-28,0	-39,6	-45,4	-59,5
15	-20,4	-30,1	-52,8	-46,2	-20,4	-30,2	-72,9	-50,1	-19,2	-16,5	-29,2	-29,3
Average	-30,0	-53,5	-50,6	-62,6	-25,4	-46,2	-41,9	-56,6	-20,9	-34,7	-28,0	-39,8
SD	12,4	22,5	14,9	22,8	8,0	16,9	17,0	27,7	5,5	13,4	12,0	17,1

As can be seen from the averages the speeds got higher for all muscles when the load increased. The difference was statistically significant for all muscles in isometric task (GM and Sol $p<0.01$ and FHL $p<0.05$) and in concentric task for FHL ($p<0.05$). The speeds were also higher in concentric tasks when compared to the isometric tasks at the 10% torque level For GM $p<0.0019$, and Sol ($p<0.05$), but not for FHL. At 30% torque level no statistically significant differences were found.

Because of missing data the N was very small in many cases. Therefore Iso 10% and Con 10% were pooled together to form variable “10% load”. Iso30% and Con 30% were similarly pooled to form “30% load”. The new pooled variables were then compared in order to see whether there are differences between the two workloads. Statistically significant difference was found for all muscles ($p< 0.01$) (Figure 16).

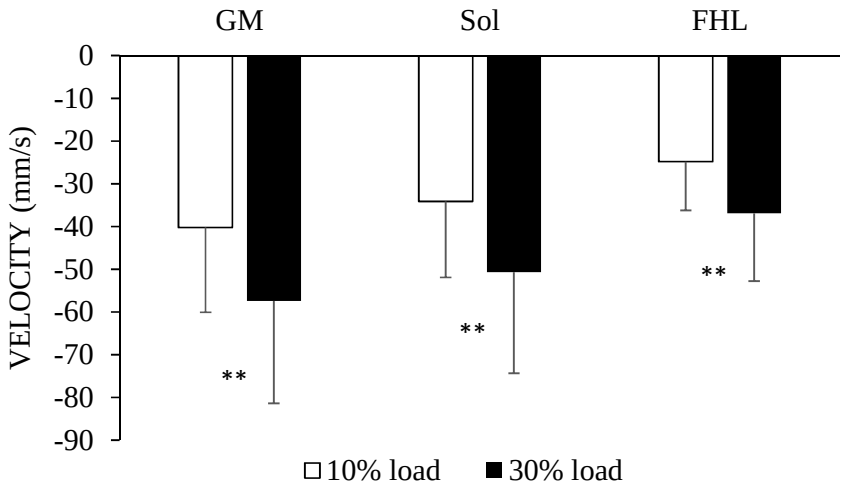

FIGURE 16. Average of peak muscle velocities in gastrocnemius medialis (GM), soleus (Sol), and flexor hallucis longus (FHL) at 10%MVC and 30%MVC. Error bars represent standard deviation. Significant differences between loads: ** $p<0.01$, *** $p<0.001$.

Similarly to the load new pooled variables were created in order to compare the two types of muscle contraction. Iso 10% and Iso30% formed the variable "isometric" and Con 10% and Con 30% formed the variable "concentric". As with the load there was a statistically significant difference between isometric and concentric tasks for all three muscles (GM $p<0.001$, Sol $p<0.05$, and FHL $p<0.01$) (Figure 17).

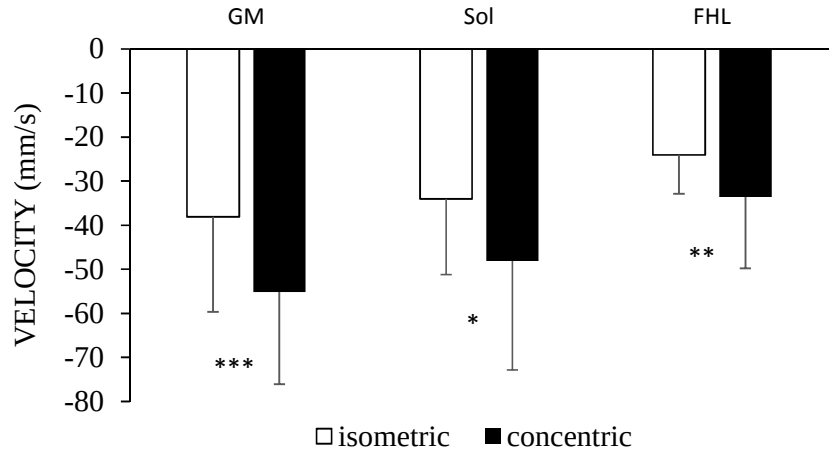

FIGURE 17. Average of peak muscle velocities in gastrocnemius medialis (GM), soleus (Sol), and flexor hallucis longus (FHL) in isometric and concentric tasks. Error bars represent standard deviation. Significant differences between loads: * $p<0.05$ ** $p<0.01$, *** $p<0.001$

In order to compare the relative contribution of the deeper muscles, velocity ratios between gastrocnemius and flexor hallucis longus as well as soleus and flexor hallucis longus were calculated. Velocity ratios were slightly higher for GM/FHL than Sol/FHL. Velocity ratios for all the subjects and the averages and standard deviations are listed below (Table 3).

TABLE 3. Gastrocnemius/flexor hallucis longus (GM/FHL) and soleus/flexor hallucis longus (SOL/FHL) velocity ratios for all subjects as well as average and standard deviation.

	Iso 10		Iso 30		Con 10		Con 30	
Subject	GM/FHL	SOL/FHL	GM/FHL	SOL/FHL	GM/FHL	SOL/FHL	GM/FHL	SOL/FHL
1	1,43	1,15	1,86	1,82	1,18	0,76	0,92	0,76
2	1,86	2,09	2,10	2,21	2,46	3,09	1,88	2,39
3	2,02	1,45	1,31	1,02	2,41	1,37		
4	1,37	1,37			2,18	1,51	2,74	2,12
6	0,63	0,61	1,41	1,18	2,03	1,43	1,52	1,12
7	1,68	1,37	1,24	0,96	1,97	1,31		
8	0,92	1,09	1,17	1,22	1,01	1,13	0,99	0,93
10	1,19	0,85	1,03	0,75	1,47	1,46		
12	1,88	1,36	2,39	1,92	1,86	1,59	1,72	1,65
15	1,26	1,06	1,82	1,83	1,81	2,50	1,58	1,71
Average	1,42	1,24	1,59	1,43	1,84	1,61	1,62	1,53
SD	0,45	0,40	0,47	0,51	0,49	0,68	0,61	0,61

As can be seen from the table above there were clear differences in the GM/FHL and Sol/FHL velocity ratios between subjects. For example the average ratio for subject 8 was 1.02 for GM/FHL and 1.09 for Sol/FHL for subject 2 the averages were 2.08 and 2.44 respectively. Figure 18 illustrates the differences between the two subjects. For subject 8 the velocities in all four tasks are very similar for all three muscles. Whereas, for subject 2 there was little to no movement in FHL in neither of the isometric tasks nor the con 10% task. For the Con 30 % task there is movement in FHL, but the velocity is much higher in the superficial muscles.

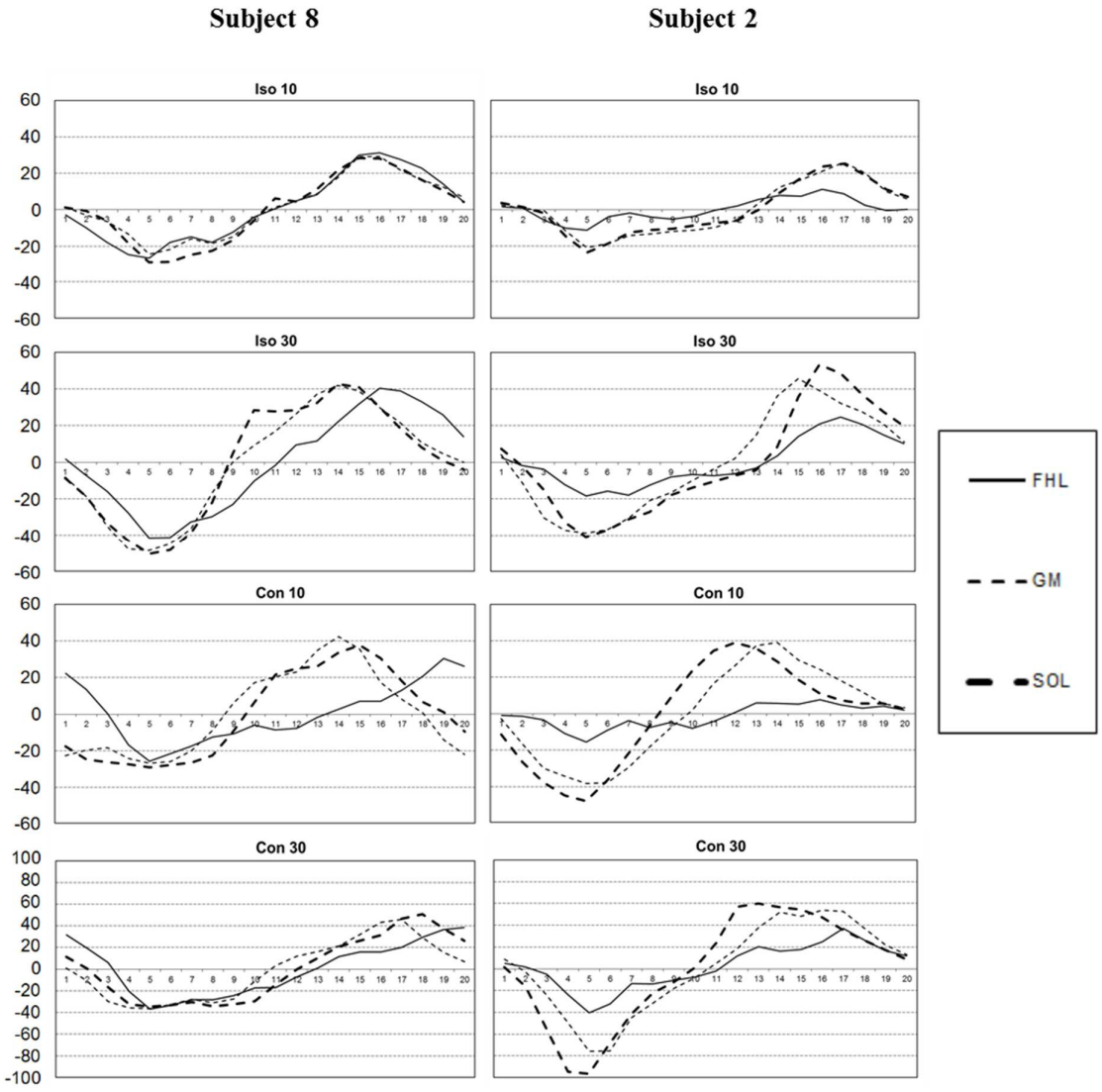

FIGURE 18. Example of muscle velocities of the three muscles gastrocnemius (GM), Soleus (Sol), and flexor hallucis longus (FHL) for two subjects in the four different tasks isometric 10% MVC (Iso 10), isometric 30% MVC (Iso30), concentric 10% MVC (Con10), and concentric 30% MVC (Con30).

The average velocity ratios in the isometric tasks were slightly higher at the 30 % force level. Being 0.16 higher for GM/FHL and 0.21 for Sol/FHL. Thus, indicating that relative contribution of the deeper muscles was smaller at 30% force level compared to 10% force level. For the concentric tasks the opposite was true. The velocity ratio was lower at 30% force level. For

GM/FHL it was 0.17 lower and for Sol/FHL 0.19 lower, which suggest that the relative contribution of the deeper muscles was higher at the higher force level. For both movement types differences were small and they were not statistically significant.

At the 10% force level the two different movement types seem to differ slightly. For GM/FHL the velocity ratio was 0.41 smaller in the isometric task compared to the concentric task. The difference was statistically significant ($p<0.05$). For Sol/FHL the ratio was 0.38 smaller in isometric compared to concentric, but it was not statistically significant ($p=0.068$). At the 30% force level the differences were opposite and not quite as big as they were at the 10% force level. For GM/FHL the ratio was 0.36 and for Sol/FHL 0.27 higher in isometric compared to concentric and there was no statistical significance.

7.3 Correlations

Average force at the 10% force level was 154.3 Nm in the EMG measurements and 144.7 Nm for the MRI. For the 30% force level they were 341.8 Nm and 234.9 Nm respectively. Correlation between the measured force in the two different measurements was good ($r=0.80$, $p<0.001$). For Gastrocnemius ($r=0.46$, $p<0.01$) and flexor hallucis longus ($r=0.61$, $p<0.001$) the EMG data correlated with peak mean negative velocity of the PC MRI. For Soleus the data from the two different measurements did not correlate ($r=0.15$, $p=0.39$) (Figure 19).

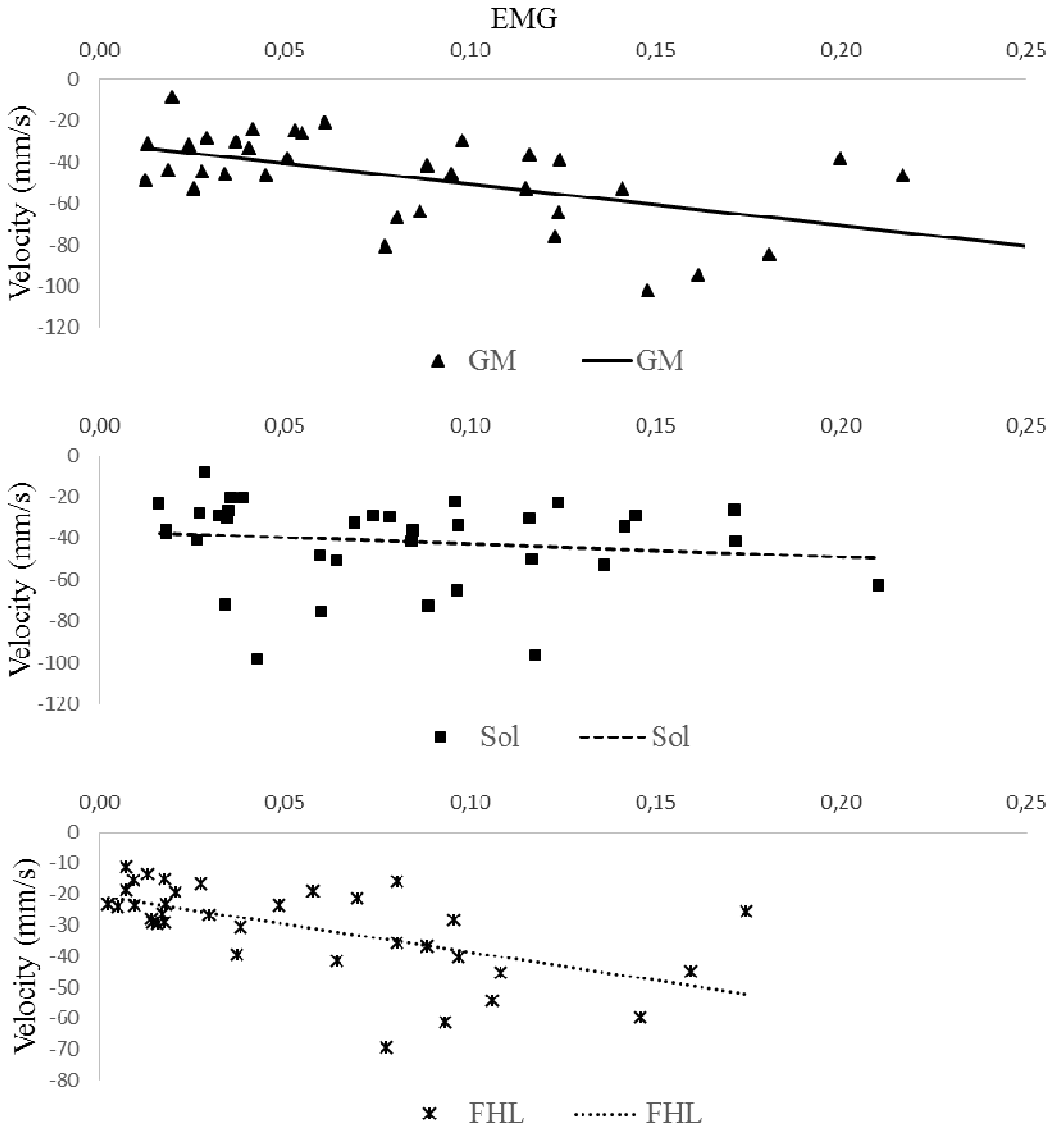

FIGURE 19. Relationship between peak mean velocity and EMG in gastrocnemius (GM), soleus (Sol), and flexor hallucis longus (FHL).

The peak negative velocity and torque had a statistically significant correlation for GM (r= -0.36, p<0.05) and for soleus (r= -0.40, p<0.05). For FHL (r= -0.32, p=0.73) the torque and peak negative velocity did not correlate. Correlations between torque and EMG were quite similar. For GM (r= 0.34, p< 0.05), soleus (r= 0.32, p=0.056), and FHL (r= 0.36, p<0.05) (Figure 20).

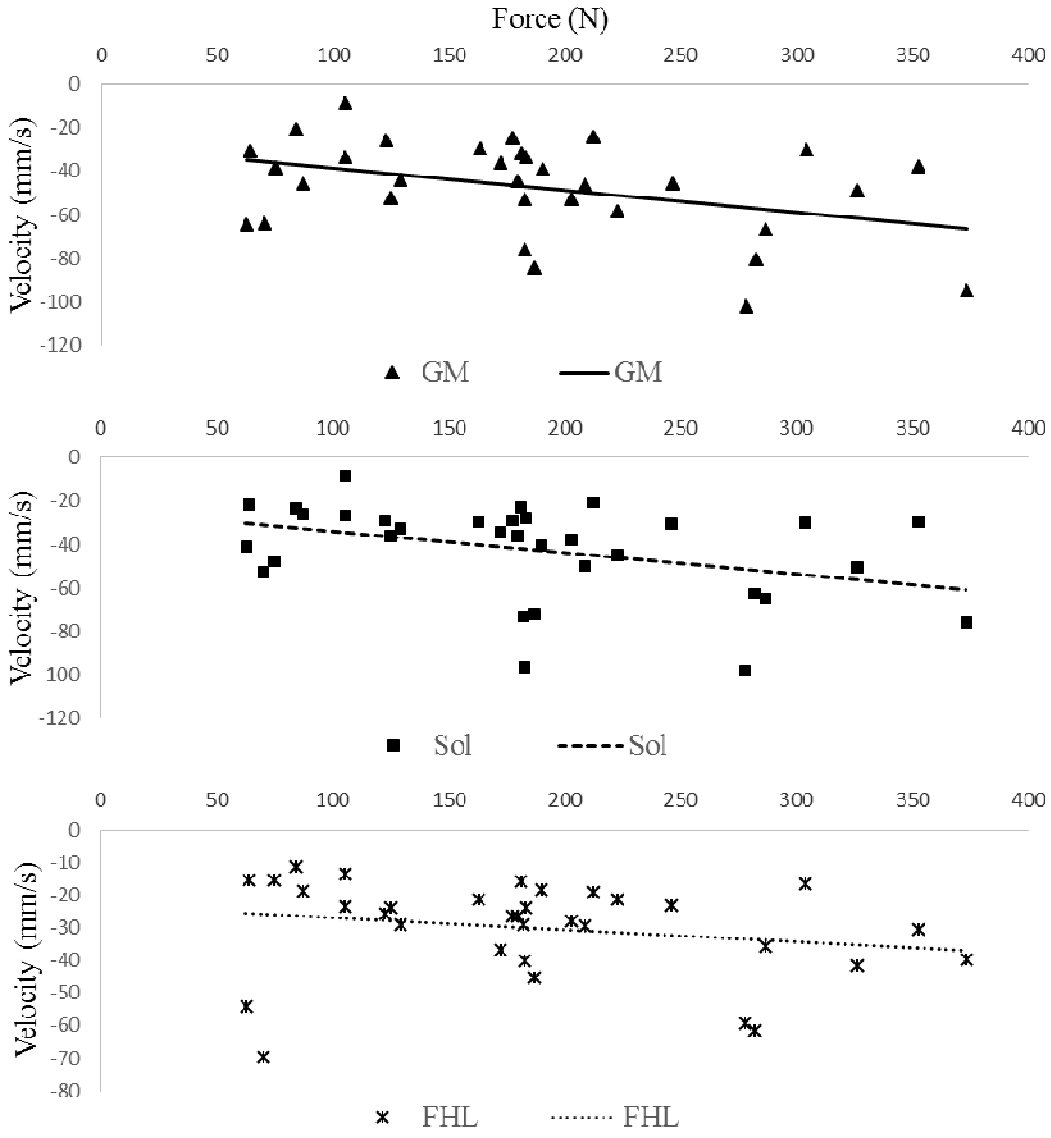

FIGURE 20. Relationship between Force and peak mean velocity of gastrocnemius medialis (GM), soleus (Sol), and flexor hallucis longus (FHL)

8 DISCUSSION

In this study cine PC MRI was used to measure the velocity of muscle tissue during isometric and concentric plantar flexion tasks at torque levels of 10% and 30% of maximal voluntary contraction. Main purpose of the study was to examine whether there are differences in the way individuals use the muscles of the lower leg in order to produce plantar flexion. To see if some people have a greater relative contribution towards the net torque from deeper plantar flexors, such as Flexor halluces longus, than others. Activations strategies were also looked at a group level, to examine if torque level or type of movement have an effect on the relative contribution of the deeper plantar flexors. Velocity data was also compared to EMG data gathered during another set of identical laboratory measurements, in order to see whether the two methods yield similar results.

As expected the peak mean negative velocities in the PC MRI measurements were found during the rising torque phase of the contraction cycle in every task. Velocities got higher as load increased and were higher in concentric tasks compared to isometric task. Velocity ratios had significant variation between subjects. At group level the velocity ratios were smaller in isometric task compared to concentric task at 10% torque level. At 30% force level no difference was found. There also were no statistically significant differences when the two torque levels were compared to each other. A statistically significant correlation was found between peak mean velocity and EMG for GM and FHL. For Soleus there was no correlation.

For some of the subjects the contraction velocities of the deeper plantar flexors were higher than the contraction velocities of the superficial muscles, whereas others had little to no movement in FHL. As a result there was a lot of variation between subjects in the velocity ratios. The GM/FHL ratio in the iso 10% task for example, was 0.6 for the subject showing most activity in the deeper musculature, whereas, the highest ratio was 2.0. Finni et al. (2006) had similar results when they calculated the ratio of muscle displacement during plantar flexion tasks. They also reported great variability among individuals with the differences in ratios being somewhat more pronounced, ranging from 0.4 to 5.5 for GM/FHL in an isometric plantar flexion at 20% torque level. The similar results of these two studies would support the notion that

there is considerable variability in the way people use the different muscles of the posterior compartment of the leg in order to produce plantar flexion torque.

When the velocity ratios were studied at group level the findings were conflicting. There was a statistically significant difference between isometric and concentric tasks at 10% torque level. So that FHL showed more activity in the isometric task compared to concentric. At 30% torque level however, the result was opposite, so that there was more activity in concentric task. When comparing the two torque levels the results were similarly conflicting. With isometric work the contribution of the FHL reduced when torque increased and with concentric work it increased. The conflicting results would suggest that neither torque nor type of contraction has an effect on the relative contribution. However, it's worth mentioning that missing data, especially from the concentric 30 % task, and thus a very small sample size, makes it difficult to show statistical significance. For example for the Iso 30% Con 30% comparison N was only six so no clear conclusions can be drawn from the results.

Earlier studies have shown that cine PC MRI can be used to reliably measure tissue velocities and tissue displacement. In the present study the peak mean velocity data acquired using the cine PC MRI was compared to EMG data. The two correlated with each other in Gastrocnemius and Flexor halluces longus. Other results were also similar including the similar correlations between torque and peak negative velocity and torque and EMG. This supports the hypothesis that the two methods yield comparable results and thus the peak mean velocity of muscle tissue measured with cine PC MRI could be used to assess the activity of muscles.

The fact that no correlation was found for Soleus is troubling. This, is most likely a result of a poorly placed region on interest. In this study the ROI for soleus was initially placed at around the midpoint of the muscle and due to software issues it was not possible to redo the placement. Usually the highest velocities occur close to the myotendinous junction that is closest to the joint that is moving (Asakawa et al. 2003). Finni et al. (2006) tested different sizes and locations of the ROI and concluded that velocities are not sensitive to either as long as the ROI is located in the distal region of the muscle. For one subject there was both a distal and central ROI in the soleus. In that case the velocities were higher in the distal part of the muscle when compared to the middle part. This supports the findings of earlier studies that in order to get the reliable

results the ROI needs to be placed at the distal end of the muscle as it was for the two other muscles MG and FHL. Another problem when comparing the two methods is the validity of the FHL surface EMG. Bojsen-Møller et al. (2010) have shown that surface EMG of FHL can measured but great care needs to be taken in order to minimize crosstalk from the soleus.

The results of this study as well as other studies show that PCMRI can be used to measure and asses the activity of muscles. It is especially useful as a non-invasive method for measuring the activity of deeper muscles that can't be measured using surface EMG. However there are some limitations that significantly limit the feasibility of the method. Most of which are a result of the high number of repetitions that is needed in order to produce the two sets of images. This limits the torque levels that can be used to relatively low level so that the effects of fatigue can be minimized, it's also quite time consuming, and it limits the types of tasks that can be performed, because the repetitions need to be simple and repeatable in order to minimize out of plane movement. In this study for example out of the 15 subjects only seven produced images that were good enough for further analysis in the Con 30 % task. High cost associated with MRI and the strong magnetic field that limits the use of conventional materials and machinery are also significant factors.

Some of these problems can be solved by using real time PC MRI. Real time PC MRI has mostly been used to measure the cardiac blood flow, but Asakawa et al. 2003 were able to measure muscle tissue velocities of biceps brachii and triceps brachii during elbow flexion and extension. They concluded that further development is needed but that it may provide a useful method of measuring muscle activity without some of the issues related to cine PC MRI.

To conclude it seems clear that individuals have a great deal of variability in the degree to which they activate the different muscles of the posterior compartment of the lower leg when producing plantar flexion torque. Based on the results of the present study neither type of movement task nor torque level seem to have an effect on the relative contribution of the deeper musculature.

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