FASCICLE-TENDON INTERACTION IN V2 SKATE CROSS-COUNTRY SKIING; A CASE STUDY

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ABSTRACT

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Stretch-shortening cycle is widely studied movement pattern in locomotion. To understand how it is utilized in muscle-fascicle level ultrasound (US) measurements are needed. One previous study has been carried out which provided the muscle-tendon level information during cross-country (xc) skiing (Ishikawa, Sano et al. 2010). Purpose of this study was to carry out a pilot measurement and provide unique muscle-fascicle level data during V2 skate xc-skiing as well as give further suggestion for the following measurements.

One experienced skier carried out measurement in Vuokatti ski tunnel. Measurements consisted of two measurement sets, in between fatiguing 20k race simulation was carried out. In the measurements muscle activity (EMG) and US from vastus lateralis (VL), medial gastrocnemius (MG), triceps brachii (long head) (TRI) and rectus femoris (RF) were recorded in a normal and a fatigued conditions in a different velocities. Muscle based data was combined to the motion and force data for the final analysis.

Uniformity of the trails was achieved well in terms of velocity and maximal forces. Fatigue did not change achieved velocities between MAX and MED condition (MAX: -0.6%, MED:-1.3%). Muscle activation pattern did not change within the muscle, however, all measured muscles showed different phase pattern respect to the lengthening direction. In muscle-tendon analysis TRI and VL muscles stretched more with increasing velocity. Biarticular muscles RF and MG did not show clear change in behavior. Fatigue did not change clearly muscle tendon behavior.

Results suggest that SSC is main method for TRI and VL muscles to increase the performance during V2 xc-skiing. Biarticular muscles (MG and RF) showed possibly some stretch but behavior did not clearly change with increasing velocity. Fatigue did not change muscle-fascicle behavior clearly, even though lower aEMG levels and shifts in force production in fatigued condition suggest that at least some fatigue was achieved. However, results are highly experimental and serve only as a pilot study. In the following measurements is important to select and attach the US probes more carefully to ensure better quality of US measurements. Measurement setup should be build more carefully to ensure better integrity and quality of the data collection.

Keywords: Cross-country skiing, skating, stretch-shortening cycle, muscle-tendon interaction, ultrasound

TIIVISTELMÄ

Lemmettylä, Teemu 2014. Lihas-jänne kompleksin toiminta V2 -hiihtotekniikan aikana. Biomekaniikan pro gradu -työ, syksy 2010. Liikuntabiologian laitos, Jyväskylän yliopisto, 68 s.

Venymis-lyhenemis –sykli (SSC) on laajalti tutkittu liha-jänne -kompleksin (MTU) toimintamalli ihmisen liikkumisessa. Jotta SSC toiminta voidaan ymmärtää, lihaksen toiminta tulee mitata ultraäänen (US) avulla. Aiemmin yksi tutkimus on käsitellyt MTU:n toimintaa hiihdon aikana perinteisellä hiihtotavalla (Ishikawa, Sano et al. 2010). Tämän tutkimuksen tavoitteena on tarjota ainutlaatuinen kokeellinen tulos MTU:n toiminnasta vapaan hiihdon V2- tekniikan aikana, sekä tarjota suosituksia tulevaa tutkimusta varten.

Tutkimuksessa yksi kokenut hiihtäjä suoritti protokolla Vuokatin hiihtotunnelissa. Protokolla koostui kahdesta eri mittauskerrasta, joiden välissä suoritettiin 20 km mittainen hiihtokilpailusimulaatio. Mittauksissa mitattiin lihasaktivaatio (EMG) ja lihaksen pituus (US) vastus lateralis (VL), medial gastrocnemius (MG), triceps brachii (long head) (TRI) ja rectus femoris (RF) lihaksista, normaalissa ja väsyneessä tilassa, useilla eri nopeuksilla. Lihas tiedot yhdistettiin liike- ja voimamittausten tuloksiin lopullista analyysia varten.

Suoritusten yhtenäisyys säilyi hyvänä mittauksissa maksimivoimien ja nopeuden valossa. Väsymys ei aiheuttanut muutosta MAX ja MED nopeuksissa (MAX: -0.6%, MED:-1.3%). Lihasten aktivoituminen säilyi samana nopeuden muuttuessa. Kuitenkin, kaikkien lihasten aktivaatiotasot olivat erilaisia suhteessa lihaksepituuden muutoksen suuntaan ja syklin vaiheeseen. Lihas – jänne tasolla TRI ja VL lihakset venyivät enemmän nopeuden lisääntyessä. Kaksi niveltä ylittävät lihakset RF ja MG eivät osoittaneet selvää muutosta toiminnassa nopeuden lisääntyessä. Väsymys ei muuttanut lihas-jänne kompleksin toimintaa selkeästi.

Tulosten mukaan SSC on tärkeä toimintamalli TRI ja VL lihaksille nopeuden kasvaessa V2 -tekniikan aikana. Kahden nivelen yli menevät lihakset RF ja MG eivät osoittaneet yhtä selvää muutosta eri nopeuksilla. Väsyminen ei muuttanut lihas-jänne kompleksin toimintaa selkeästi, vaikka aEMG tason lasku ja muutokset käsine ja jalkojen voimantuotto suhteissa viittasivat väsymykseen. Saadut tulokset ovat erittäin kokeellisia ja toimivat esitutkimuksena tuleville mittauksille. Tulevissa tutkimuksissa on kiinnitettävä tarkempaa huomiota ultraäänisensorin valintaan ja kiinnitykseen paremman mittauslaadun varmistamiseksi. Myös mittausalue on suunniteltava tarkemmin, jotta kaikki halutut mittaukset saadaan kerättyä kaikilla halutuilla nopeuksilla.

Avainsanat: Maastohiihto, V2 -tekniikka, venymis-lyhenemis -sykli, lihas-jänne kompleksin toiminta, ultraääni

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ABSTRACT

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REVIEW OF LITERATURE

1 INTRODUCTION

Cross-country (xc) skiing has been known for centuries. Originally it was a method for human transporting in artic areas. Modern xc-skiing is winter sports were skiers propel themselves through the marked track in variable terrain. Xc-skiing consists of two different techniques classic and skating which both consist of different sub techniques. Equipment and track preparation play a big role in modern xc-skiing defining largely the changes in xc-skiing in last decades. Modern cross country skiing has experienced two big changes. First one was the implementation of plastic ski in the 70's and second one was the implementation of skating technique in 80's (Kirvesniemi 1996). Development in xc-skiing have also changed remarkably metabolic costs of xc-skiing and racing velocities. In addition, race types have changed from interval starts towards mass start and sprint races. Change in race types favors skiers who can achieve high skiing velocities and maintain submaximal speed with lower effort. Development has created a demand of faster strategies in xc-skiing. It can be said that the need of speed had changed physiological and biomechanical demands of the modern xc-skier. (Formenti, Ardigo et al. 2005; Holmberg, Lindinger et al. 2005)

Natural way to solve enhanced demand of force/economy muscle tendon level is movement pattern called stretch shortening cycle (SSC). In SSC movement pattern activated muscle tendon unit (MTU) is stretched before concentric action to produce more enhanced muscle work. Naturally SSC occurs in human locomotion. For example running is an exercise where SSC naturally improves performance (Kyrolainen, Avela et al. 2005). In xc-skiing the use of SSC has been identified e.g. in the use of counter movements (Komi and Norman 1987) and as a method to achieve faster skiing velocities (Perrey, Millet et al. 2000). To understand how MTU behaves in tendinous tissue (TT) - fascicle level during ground contact of locomotion, muscle behavior can be measured with ultrasound device (Ishikawa, Finni et al. 2003). MTU behavior is widely studied in human locomotion. However there is lack of studies in xc-skiing (Fukunaga, Kawakami et al. 2002).

Aim of this study is to provide unique muscle tendon level information of muscle tendon interaction during V2 skate xc-skiing in vivo. In the study muscle tendon data is combined to kinematic data and muscle activity. Data will be provided in three different speeds in fatigued and non-fatigued situation. Previously one unique study has been done in Vuokatti where muscle activity, forces and MTU behavior were measured during xc- skiing. In a study of Ishikawa, Sano et al. (2010) classical skiing MTU behavior was studied in slight uphill. Current study was the first one to show MTU behavior in skate xc-skiing.

2 STRETCH-SHORTENING CYCLE

2.1 Definition of SSC

Stretch-Shortening Cycle (SSC) is a movement pattern which combines elastic properties, three action types of muscle and reflex action to produce more effective concentric action. SSC is common movement in human locomotion. Locomotion like running, walking and hopping where external forces lengthen the muscle is favorable to SSC to occur. (Komi 2000)

SSC is defined as a movement pattern where active muscle (isometric phase) is stretched (eccentric phase) before shortening (concentric phase) (Norman and Komi 1979; Komi 1984; Nicol, Avela et al. 2006). Komi (1984) showed the utilization of SSC in human running (figure 1). SSC in running involves, preactivation, stretch and shortening. Preactivation occurs before ground contact. Activated muscle is stretched in braking phase before “concentric” push phase. SSC type of movement pattern has several advantages. (1) Muscle can perform more positive work and produce more power. (2) Submaximal task can be done more economically. (3) Preactivation levels can be matched to expected level to minimize unexpected delays (Komi 2000; Komi, Ishikawa et al. 2011).

Effective utilization of SSC needs three fundamental conditions: (1) Well-timed preactivation, (2) short and fast eccentric phase and (3) immediate transition from stretching to shortening phase (coupling time) (Komi and Gollhofer 1997). In optimal situation SSC provides spring-like interface between body and environment in natural locomotion (Cavagna and Kaneko 1977).

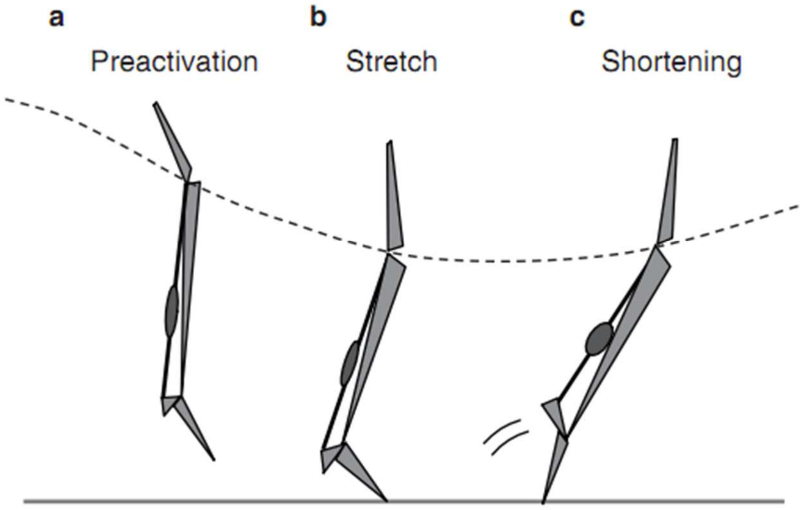


FIGURE 1. Three phases of SSC during human running. (A) Preactivation; (B) Stretching; (C) Shortening. (Komi 1984)

Time wise mechanisms contributing SSC performance have been under discussion until 21st century. SSC was first time introduced by Asmussen and Sørensen (1971) as a wind up movement and named as SSC by Norman and Komi (1979). However a question was raised in 1997 by Ingen Schenau if reflexes or elastic energy can be enhancing SSC performance. (Ingen Schenau, Bobbert et al. 1997b; Ingen Schenau, Bobbert et al. 1997a)

2.2 Basic muscle mechanics

A classic Hill's-muscle model models a muscle tendon unit (MTU). Hill's model consist of three elements: (1) serial elastic element, (2) parallel elastic element and (3) contractile element (figure 2). Contractile element illustrates muscle fibers that produce contractile action. Parallel elastic element illustrates the muscles properties to store force in the muscle fibers. Serial elastic component illustrates tendons which can store force but not perform contractile action. (Hill 1938) The fundamental idea of the model is that force produced by contractile component is transmitted through serial elastic component to the joint. In stretching situation force can be stored in parallel and serial elastic components. (Zajac 1989)

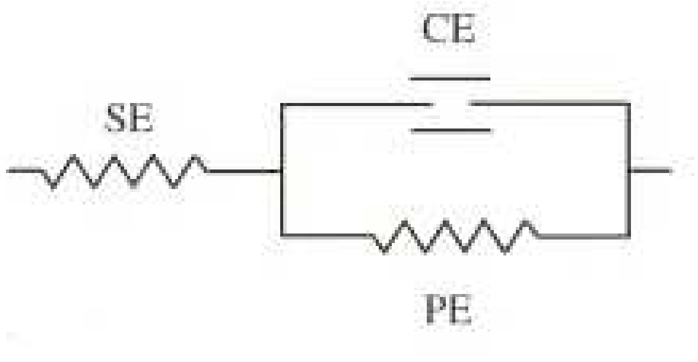


FIGURE 2. Hill based muscle model consist of three elements; contractile element (CE), serial elastic element (SE) and parallel elastic element (PE). (Scovil and Ronsky 2006)

Human muscle can perform three types of muscle actions; *isometric*, *concentric* and *eccentric*. During isometric contraction muscle action joint angle of the desired joint does no change. Concentric action causes flexion and eccentric action respectively causes extension of the desired joint. *Force-velocity curve* illustrates the ratio between action velocity and force that muscle can perform. Highest force production can be achieved in eccentric work. Force production is lowest in the fast concentric work (figure 3). (Wilkie 1949) Joint angle affects also to force muscle can produce. Muscle performance is highest near the middle of the joint angle range because of the optimal sarcomere lengths. (Enoka 2008)

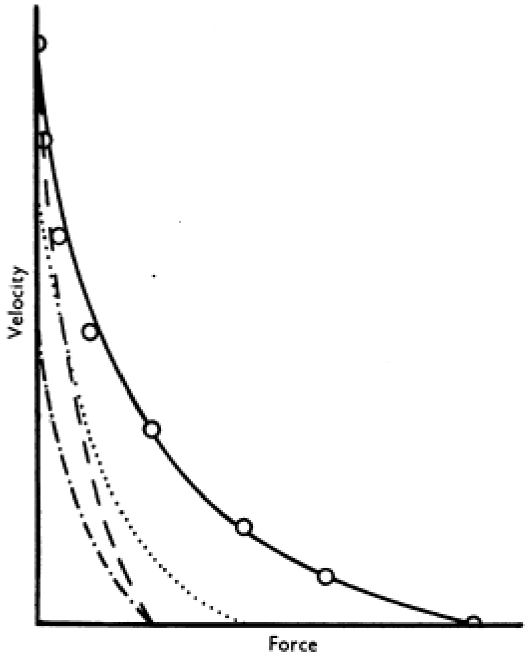


FIGURE 3. Force-velocity relationship for muscle in concentric action (Wilkie 1949).

2.3 Utilization of elastic energy

As it was presented in the Hill’s muscle model TT and fascicle can store force in MTU (Asmussen and Bonde-Petersen 1974). Moreover tendon has viscoelastic properties meaning that tendon comes stronger and stiffer when more force is applied to the tendon (Welsh, Macnab et al. 1971). Force that tendon can return is almost linear to prestretch intensity (Ker 1981). Furthermore force stored to the tendon can be restored faster than muscle fiber can produce voluntary (Bennett, Ker et al. 1986). Approximately 93 % of work done on the stretching phase can store in the tendon. 7% of the stored work is lost in heat dissipation (Bennett, Ker et al. 1986). It is suggested that more compliance tendons can store more energy to be used in concentric phase after stretch (Kubo, Kanehisa et al. 2005). Utilization of elastic energy can be shown e. g. in difference of squat jump (SJ) and counter movement jump (CMJ). Higher jump heights can be achieved with counter movement. Both jumps involve stretch of the tendon but countermovement of CMJ loads tendon more efficient and allows to store more force to be returned in concentric phase. (Bobbert, Gerritsen et al. 1996; Finni, Komi et al. 2000) In the figure 4 tendon forces have been plotted during CJ and CMJ. Results have been compared to force – velocity curve of the same muscle. Difference in curves can be explained as the elastic properties of the MTU. Elastic component length changes faster than the length of muscle fascicle. Length change of the elastic component makes it possible to muscle fibers to work near-isometric. (Finni, Ikegawa et al. 2003)

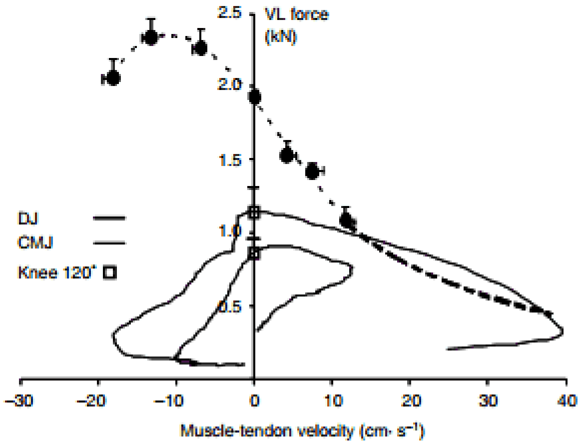


FIGURE 4. Patella tendon force in drop jump (DP) and in counter movement jump (CMJ) plotted against patella tendon force in isokinetic curve in respect of 120 degree knee angle (Finni, Ikegawa et al. 2003).

Cavagna, Saibene et al. (1965) showed in study with frog's *sartorius* muscle that shorter interval between stretching and shortening of the muscle leads to greater positive work arguing that extra work comes mainly from elastic energy. Coupling time is critical for the force restore. Force is stored to the tendons and myofilaments. Stored force is lost due the viscoelastic nature of the tendon when time interval between eccentric and concentric actions is prolonged. Influence of coupling time has been shown e.g. in human knee extensor muscle. Force potentiation is greatest when no delay exists between eccentric and concentric phases (figure 5). (Komi, IOC Medical Commission. et al. 2003)

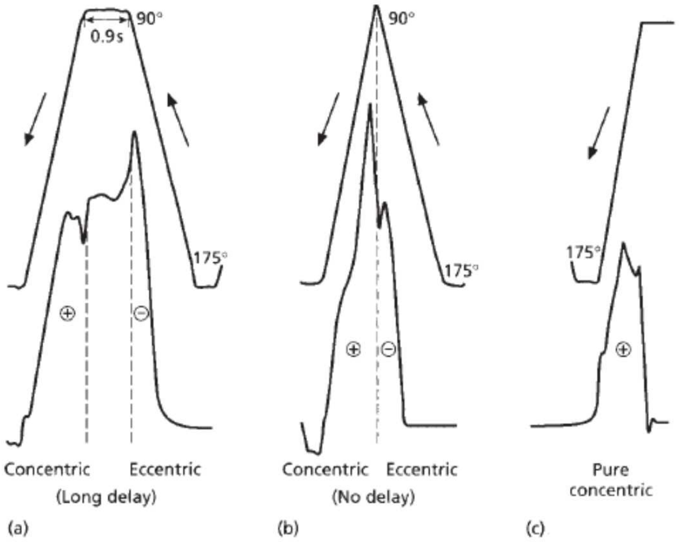


FIGURE 5. Knee angle and produced force. Counter movement and delay in movement direction change is altered. Produced force is greatest in non-delay situation. (Komi 1983)

2.4 Stretch reflex

Stretch reflex (SR) occurs when muscle is exposed to rapid stretch. The function of SR is e.g. to react unexpected displacements of the joint. SR is evoked by monosynaptic 1a excitation and is regulated in a motor neuron pool according to sensory feedback. SR consists of two components; short (M1) and medium (M2). Latencies of components can vary. M1 latency exists near 30ms after ground contact depending on muscle. M2 occurs later near 60ms after ground contact. Voluntary activation can exist earliest 150ms after unexpected displacement (Enoka 2008, 261). Studies made in ischemic condition show a reduction in M1 activity. It was argued that reduction in M1 activity was due reduced 1a afferent excitation. (Komi and Gollhofer 1997) It is suggested SR plays important role in joint stiffness regulation In SSC by balancing excitatory and inhibitory feedback (Cronin, Peltonen et al. 2008).

M1 can be observed from EMG measurements. Figure 6 shows EMG measurement of MG muscle during sledge jump contact phase. M1 is clearly visible 40ms after ground contact. Intensity effects to SR activity. Highest M1 activity is found in high but submaximal intensities. Higher prestretch intensities (e.g. drop heights 80-140cm) can cause reduction in M1 which is caused most likely by Golgi tendon organ inhibition. It is argued that reduced reflex activity can serve as protection from muscle and tendon injury. (Horita, Komi et al. 1996)

SR existence and contribution is showed in different situations. In a study where ankle was stretched in different speeds, occurrence of SR increased Achilles tendon force by 261% (Nikol & Komi, 1998). Running in different speeds showed that role of SR can vary in same exercise in different speeds (Ishikawa & Komi, 2007). M1 and M2 components are presented in figure 6 in drop jump situation (Horita, 1996).

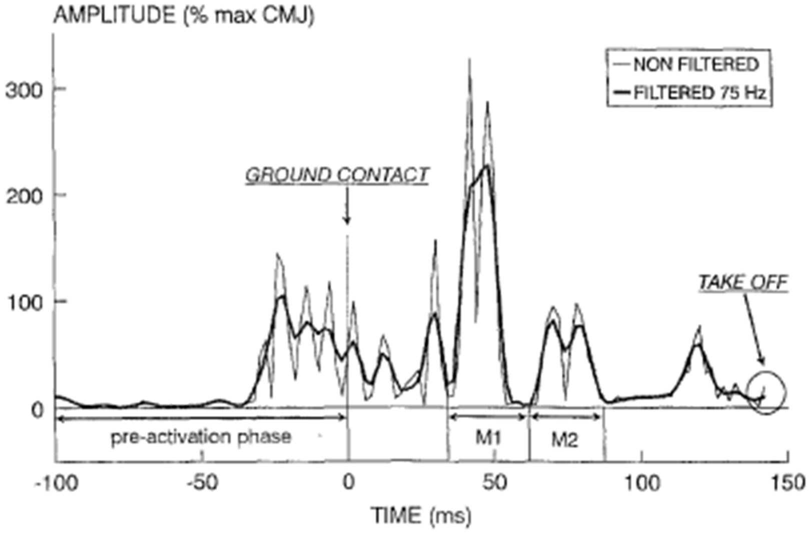


FIGURE 6. Rectified (thin line) and filtered (thick line) EMG activity during drop jump. M1 and M2 components of stretch reflex are marked with arrows. (Horita, 1996)

2.5 Requirements of SSC

In SSC situation well timed preactivation is crucial to effective SSC performance (Komi and Gollhofer 1997). Activation of the muscle before ground contact was first introduced by Jones and Watt (1971) on a study of human hopping and stepping movements. Pre activity was presented as centrally programmed pre-landing activity. Increased pre-activity is associated with increased impact loads in locomotion (Komi

2000). Higher pre activation with increased loads is documented in studies e.g. xc skiing (Lindinger, Holmberg et al. 2009), running (Kyrolainen, Avela et al. 2005) and jumping (Ishikawa, Niemela et al. 2005) .

Muscle fibers *length-force* relation shows importance of optimal sarcomere length in force production (Enoka 2008). Pre-activation may play an important role matching the muscle fiber lengths to efficient SSC performance. Pre-activation regulates the tendon stretch during the stretch phase (Fukunaga, Kawakami et al. 2002). Increased muscle pre-activity plays a role in stretch reflex sensitivity. One mechanism is that pre activation promotes γ -activity which leads to increased stretch reflex sensibility. (Kyrolainen, Avela et al. 2005)

In locomotion SSC is widely studied as differences of EMG activity in eccentric and concentric phases. Kyrolainen, Avela et al. (2005) showed difference of running in different speed as difference in muscle action of preactivity, braking and Push-off phases (figure 7). Phases were defined from ground reaction forces according to orientation of horizontal force. Preactivity was defined as period of 100ms before ground contact. Results emphasize the importance of pre-activation with increased speed. Same method is used in xc-skiing studies (Perrey, Millet et al. 2000; Lindinger, Holmberg et al. 2009). Zoppirolli, Holmberg et al. (2013) expanded the idea of calculating activation levels to SSC phases by estimating the efficiency of SSC. In a study made in xc-skiing double poling average activations of flexion and extension are divided and result estimates the efficiency of SSC. Study proposed that those good skiers can increase efficiency of SSC with increasing speed.

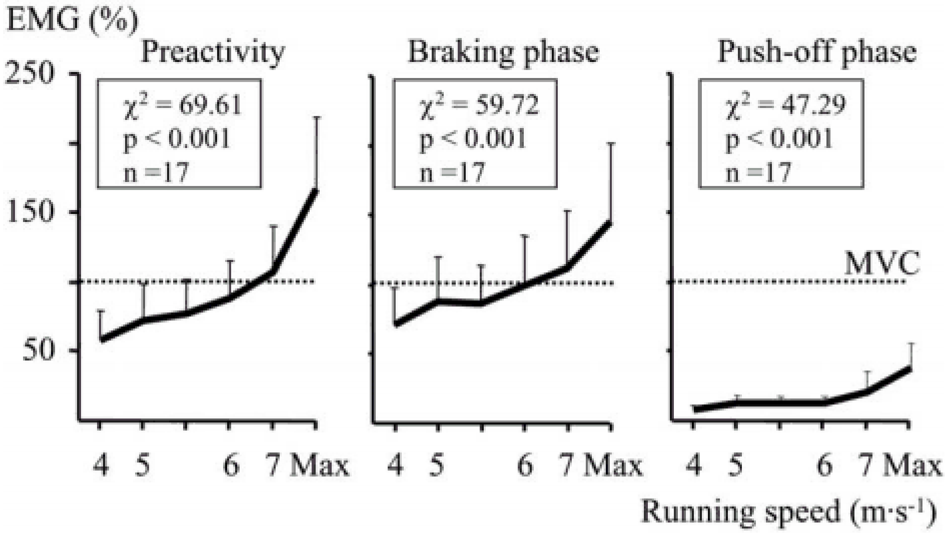


FIGURE 7. Differences in aEMG in different running speeds at preactivity, braking- and push-off phases. (Kyrolainen, Avela et al. 2005)

3 MUSCLE TENDON INTERACTION

To understand how SSC works in muscle - fascicle level muscle fiber and MTU lengths must be measured. *In vivo* muscle fascicle behavior can be studied with *ultrasound* apparatus (US). Muscle tendon unit (MTU) behavior is widely studied in locomotion like running and walking (Kawakami and Fukunaga 2006) .

3.1 Ultrasonography as a tool to study muscle tendon interaction

Ultrasonography (US) is noninvasive method to estimate skeletal muscle architecture during movement. (e.g. Finni, Hodgson et al. 2003; Hodges, Pengel et al. 2003; Loram, Maganaris et al. 2006). US measurements enable visualization of muscle thickness, muscle fiber length and pennation angles (figure 8). Figure 8 shows ultasonograms from gastrocnemius muscle and placement of US probe. Ultrasonic probe is attached longitudinally to the muscle belly. (Kawakami and Fukunaga 2006)

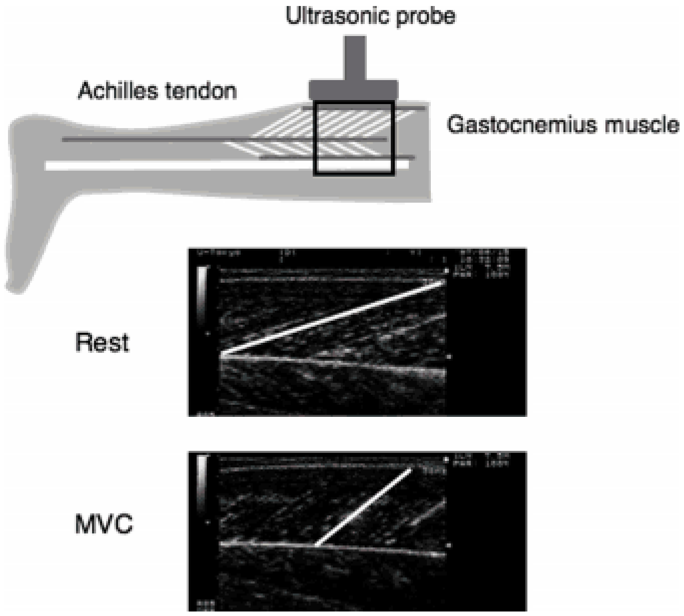


FIGURE 8. US Probe placement and longitudinal ultrasonic images of the muscle in rest and MVC from gastrocnemius muscle. (Kawakami and Fukunaga 2006)

Muscle fascicle and pennation angle analysis is a continuous frame to frame analysis. Muscle fiber length is measured tangentially between the deep and interfacial aponeurosis (figure 8). Pennation angle is defined as an angle between inner aponeurosis and muscle fiber. Figure 8 shows gastrocnemius muscle fiber in two conditions: (1) rest and (2) MVC. Tracking of the muscle length and pennation angle can be done manually with suitable software (e.g. Ishikawa, Niemela et al. 2005). Furthermore, specially made algorithms have been used to analyze the fascicle length and the pennation angle. (e.g. Loram, Maganaris et al. 2006; Lee, Lewis et al. 2008)

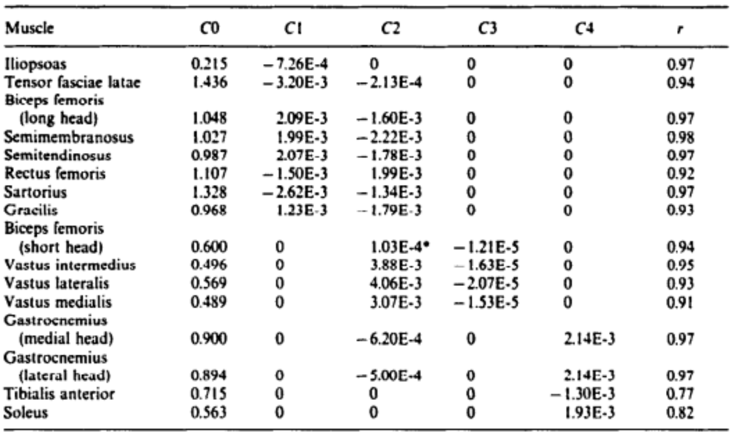
3.1.1 Modeling Muscle tendon unit

Muscle tendon unit (MTU) length is estimated with a model. A widely used model for lower extremity muscles model has been presented by Hawkins and Hull (1990). Muscle lengths are estimated using tight and shank length of subject. Lengths are estimated respect to joint angles. Formula 1 is used to estimate whole MTU length.

$$L = C0 + C1\alpha + C2\beta + C3\beta^2 + C4\phi. \quad (1)$$

Where C0-4 are regression equation constants (see table 1) and χ, β and α are hip, knee and ankle flexion angles. Equation estimates the length of the desired MTU ($\text{Length}_{\text{mtu}}$) relative to the standing state.

TABLE 1. Regression equation constants and correlation coefficients. (Hawkins and Hull 1990)



Muscle	C0	C1	C2	C3	C4	r
Iliopsoas	0.215	−7.26E-4	0	0	0	0.97
Tensor fasciae latae	1.436	−3.20E-3	−2.13E-4	0	0	0.94
Biceps femoris (long head)	1.048	2.09E-3	−1.60E-3	0	0	0.97
Semimembranosus	1.027	1.99E-3	−2.22E-3	0	0	0.98
Semitendinosus	0.987	2.07E-3	−1.78E-3	0	0	0.97
Rectus femoris	1.107	−1.50E-3	1.99E-3	0	0	0.92
Sartorius	1.328	−2.62E-3	−1.34E-3	0	0	0.97
Gracilis	0.968	1.23E-3	−1.79E-3	0	0	0.93
Biceps femoris (short head)	0.600	0	1.03E-4*	−1.21E-5	0	0.94
Vastus intermedius	0.496	0	3.88E-3	−1.63E-5	0	0.95
Vastus lateralis	0.569	0	4.06E-3	−2.07E-5	0	0.93
Vastus medialis	0.489	0	3.07E-3	−1.53E-5	0	0.91
Gastrocnemius (medial head)	0.900	0	−6.20E-4	0	2.14E-3	0.97
Gastrocnemius (lateral head)	0.894	0	−5.00E-4	0	2.14E-3	0.97
Tibialis anterior	0.715	0	0	0	−1.30E-3	0.77
Soleus	0.563	0	0	0	1.93E-3	0.82

To estimate how tendinous tissue (TT) and fascicle behave *in vivo,* estimated length$_{mtu}$ and measured fascicle information need to be combined (Figure 9). TT length (length$_{tt}$) is calculated by subtracting MTU directional fascicle area length (lenght$_{fascicle}$) from the estimated length$_{mtu}$ (e.g. Fukunaga, Kawakami et al. 2002; Hodges, Pengel et al. 2003; Ishikawa, Niemela et al. 2005). Formula 2 is used to calculate length$_{tt}$.

$$L_{TT} = L_{MTU} - L_{fascicle} \cdot \cos\alpha \qquad (2)$$

Result of the calculations is lengths for fascicles, TT and MTU. Analysis is done for MTU by comparing relative changes between TT and fascicle lengths. MTU data is often combined to other information such as EMG or forces to more complete analysis. e.g. to calculate tendon forces or to analyze activation patterns (e.g. Ishikawa, Finni et al. 2003; Ishikawa, Dousset et al. 2006)

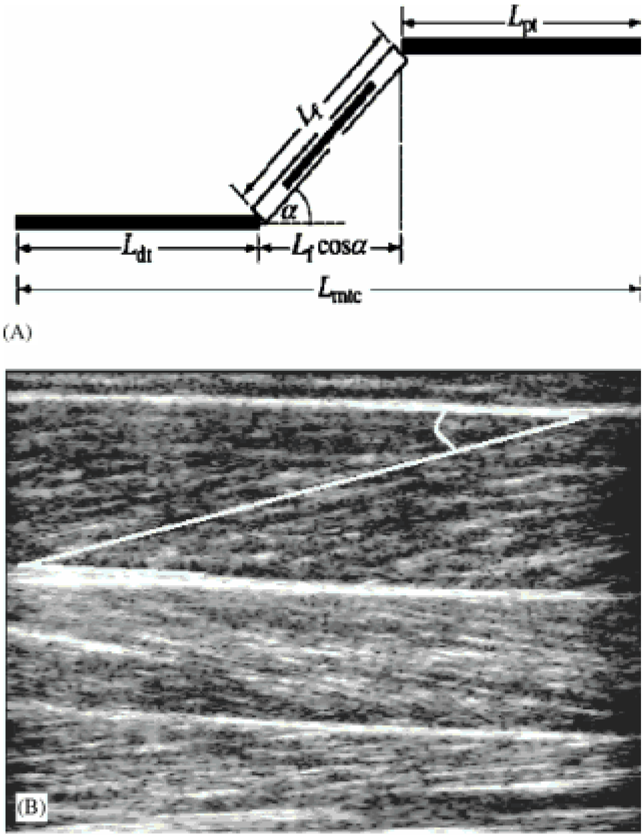


FIGURE 9. (A) Model to calculate tendon and muscle lengths. Lf is the fascular length, α is pennation angle and Lmtu is muscle tendon unit length. Lmtu is equal to Ldt + Lf cosα + Lpt. (B) Fascicle length and pennation angle measurement from US picture. (Fukunaga, Kubo et al. 2001)

3.1.2 Pennation angle and length of the Fascicle

Muscle tension and joint angles determine the fascicle lengths and pennation angles. Reeves and Narici (2003) studied tibialis anterior (TA) muscle fascicle behavior in dynamic movements. Study shows that pennation angles and fascicle lengths change in respect to joint angles, angular velocities and recruitment levels. Figure 10 shows difference in TA fascicle lengths and pennation angles in resting and MVC conditions. In resting situation fascicle length is longer and pennation angle is smaller in every measured joint angle. Higher shortening velocities showed greater fascicle lengths in comparison to lower velocities. (Fukunaga, Ichinose et al. 1997).

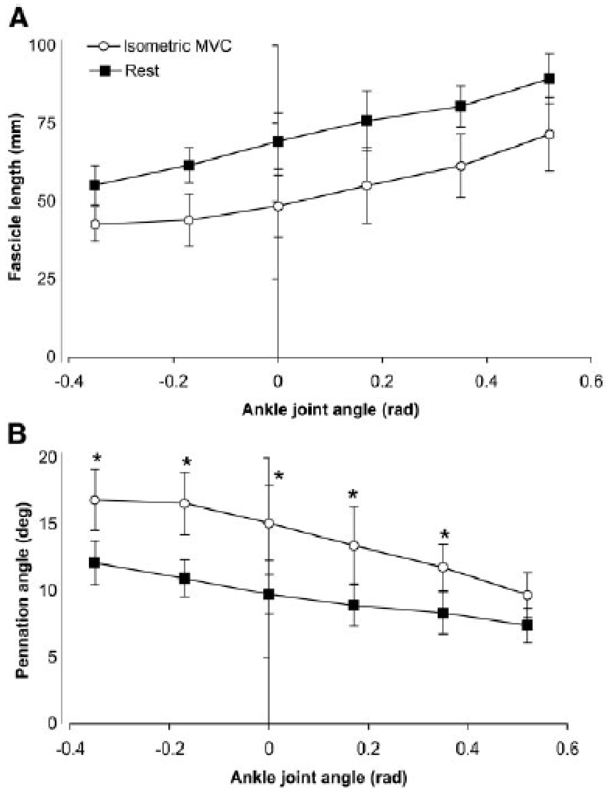


FIGURE 10. Pennation angle and fascicle length of resting and isometric MVC muscle (Reeves and Narici 2003).

3.2 Muscle and Task dependency

Muscle tendon interaction is task dependent. Task dependency is shown in comparison of counter movement and non-counter movement of plantar flexion. Medial gastrocnemius (MG) muscle fiber length in counter movement situation stays constant during eccentric phase. In non-counter movement situation MG fiber length is greater and stretch of tendinous tissue is less utilized (figure 11). Furthermore, both movements mismatch between fascicle length and joint angle. (Kawakami, Muraoka et al. 2002)

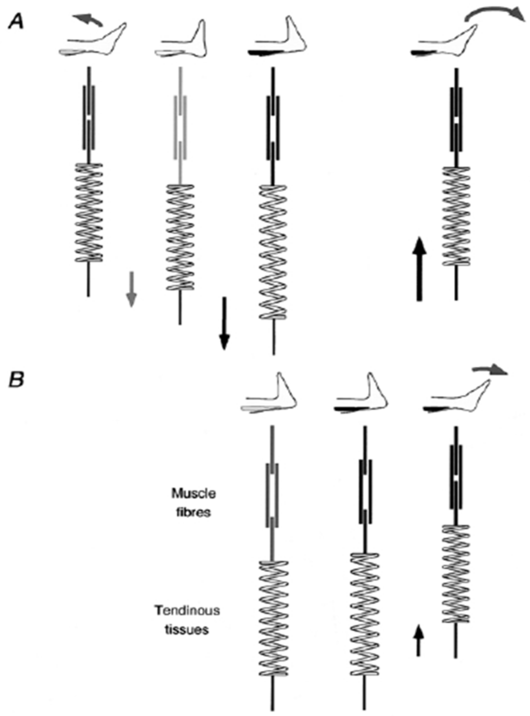


FIGURE 11. *Medial Gastrocnemius* muscle-tendon unit in CM (A) and NoCM (B) plantar flexion. Darker color indicates tension. Muscle fiber and tendinous tissue lengths are different in same joint angles. (Kawakami, Muraoka et al. 2002)

Muscle-tendon units can behave differently in same task. Figure 12 shows drop-jump situation in two different intensities. In a study done for vastus lateralis (VL) and medial gastrocnemius (MG) VL muscle behaves as expected; stretching and shortening. Respectively MG fascicle only shortens. Similar MTU behavior cannot be generalized to all muscles in TT – fascicle level. Fascicle behavior may be modified in respect to use e.g. intensity or fatigue. Function type of MTU effects to muscle behavior in dynamic situation. Bi-articular muscles like MG are less likely to show SSC type of movement pattern compared to mono articular muscles like VL and SOL. (Ishikawa 2005)

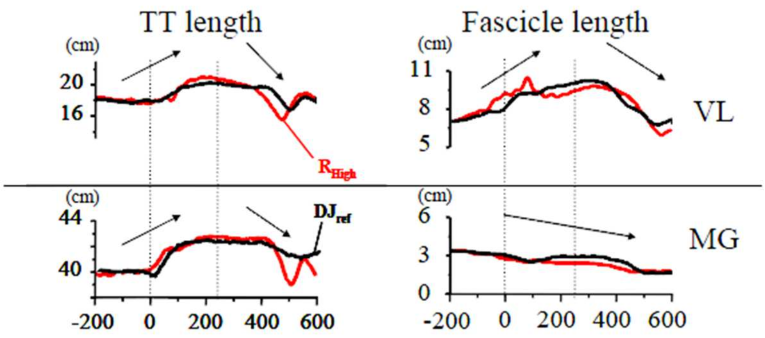


FIGURE 12. Vastus lateralis (VL) and medial gastrocnemius (GM) tendinous tissue and fascicle length during drop jump in high (red) and medium (black) intensities. Fascicle length behavior is different between two muscles in same task. (Ishikawa 2005)

TT - fascicle behavior can change when intensity of exercise changes. Generally higher utilization of TT recoil is possible when loading intensity is higher. However too high intensity leads to inhibition in muscle function (Ishikawa 2005). Behavior can be shown in short contact exercise like drop jump where an optimal point for recoil can be found. Jump height increases with dropping height to a certain point, but higher intensities cause decrease in jump height. Performance have been proposed to degrease due the inhibitory signal of Golgi tendon organ other possible limiter is limitations in coupling time of cross bridges. (Ishikawa, Niemela et al. 2005)

3.3 TT – fascicle behavior in locomotion

Cavagna and Kaneko (1977) studied mechanical properties of level walking and running. Results suggested that maximal efficiency in walking is achieved in intermediate speeds. Respectively in running mechanical efficiency increased with increasing speed. Study proposed an idea that locomotion like running is dominated by elastic component of MTU. In more detailed comparison where forces, EMG and TT-fascicle behavior was compared clear difference in utilization of TT was shown (figure 13). EMG measurements show difference in activation pattern. Highest activity in running can be found during preloading phase. Respectively highest activation in walking is during push of phase. In TT – fascicle level TT is more stretched during braking phase but returns to the same length in the end of the push of phase. (Ishikawa, Pakaslahti et al. 2007)

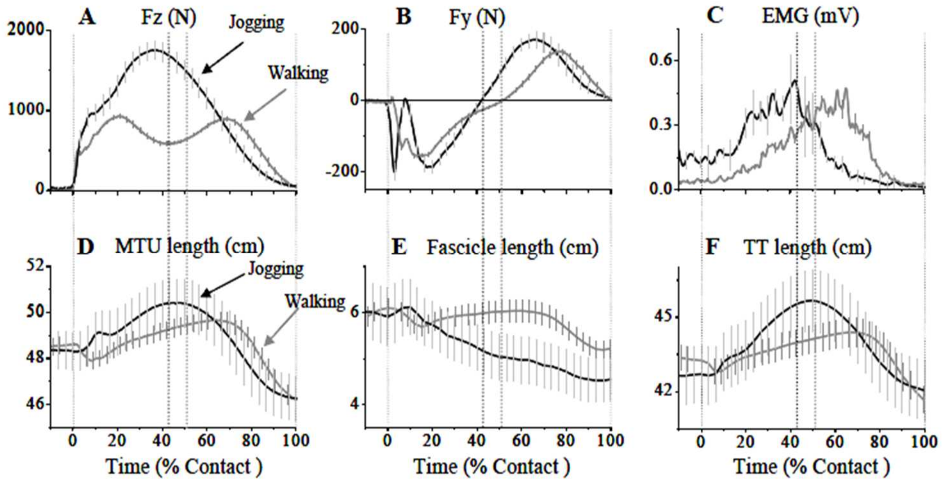


FIGURE 13. Time course data during ground contact of on human walking and jogging from gastrocnemius muscle-tendon unit. EMG is measured form medial gastrocnemius. Dotted line indicates change from braking to pushing phase. (Ishikawa, Pakaslahti et al. 2007)

Two different strategies can be characterized for MG muscle TT – fascicle behavior during walking and running. (1) Catapult action in walking meaning that during walking stance phase tendon stretches and fascicle stays almost isometric. In the end of the pushing phase tendon is released (Fukunaga, Kubo et al. 2001; Ishikawa, Pakaslahti et al. 2007). (2) Spring like action in running. Running and hopping are movements where tendon is stretched during braking phase and shortens during push off phase. (Ishikawa, Pakaslahti et al. 2007)

Role of the stretch reflex (SR) can be seen in TT - fascicle behavior. SR can regulate the tension in the TT. Ishikawa and Komi (2007) published a study where TT – fascicle behavior was studied in running with different intensity (speed). Figure 14 shows the MTU and fascicle behavior during running contact phase. Results suggest that the role of SR can be different in different intensities due to the shift of SR timing from the middle of the stance phase in slow speed to the end of the stance phase in fast speed.

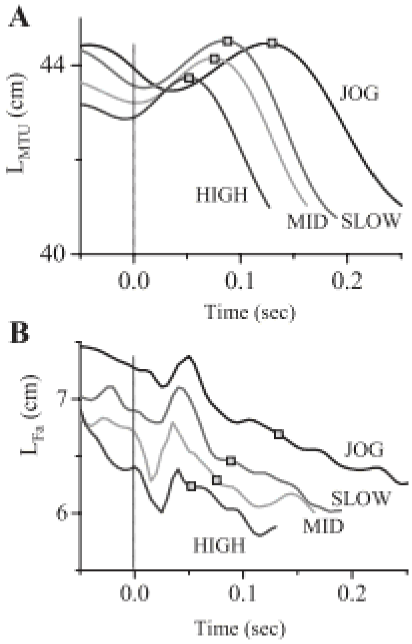


FIGURE 14. MTU and fascicle lengths at different speeds of running. (Ishikawa and Komi 2007)

4 FATIGUE IN SSC EXERCISES

Fatigue is defined e.g. as failure to maintain the requested force (Edwards 1981). Fatigue can be caused by intensity or duration of the exercise (Pasquet, Carpentier et al. 2000). Fatigue induced by SSC exercise loads neuromuscular system more comprehensive mechanically and metabolically. (Avela, Kyrolainen et al. 1999)

4.1 Acute fatigue after SSC exercise

Komi (2000) summarized muscle functional deterioration in SSC performance (figure 15). Deteriorated neuromuscular system leads to increased work during concentric phase. In other words fatigue reduces elastic energy usage and it leads to increased concentric work to main the required work load.

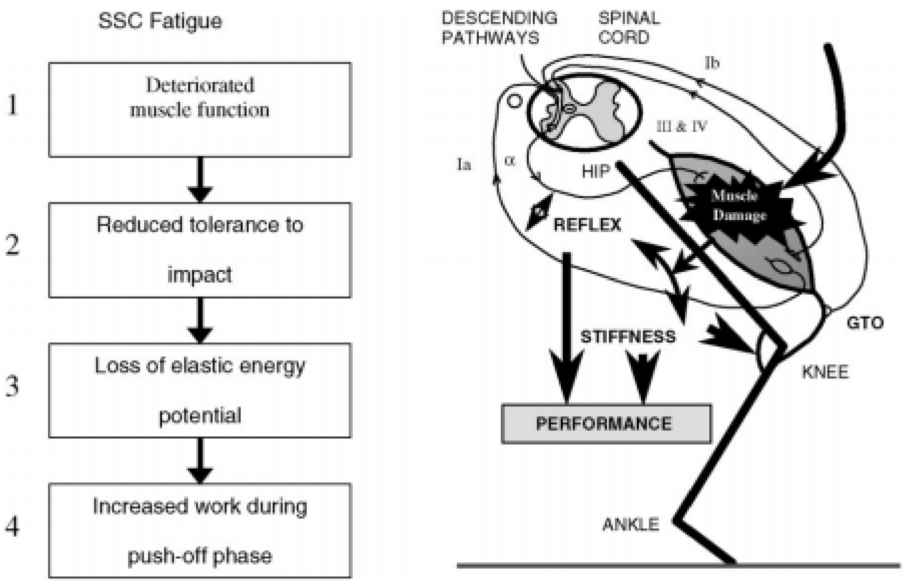


FIGURE 15. Deteriorated muscle function leads to smaller utilization of elastic energy and increased work during positive work. (Komi 2000)

In comparison of fatigue induced by SSC and isometric exercise acute response can be similar. Toumi, Poumarat et al. (2006) compared squat jump, drop jump and isometric performance after isometric and SSC exercises. Study did not suggest any significant differences between exercise types. However in comparison of concentric and SSC performance after exhausting SSC exercise the differences is clear. Performance in SSC exercises is depleted more compared to concentric performance (Horita, Komi et al. 2003). Long lasting low intensity SSC exercise like marathon run deteriorate muscle performance and SSC utilization. Figure 16 shows VL and SOL muscle activation and force before and after marathon run. Long lasting SSC exercise reduces significantly M1 reflex area as well as has significant effect to force. (Avela and Komi 1998; Avela, Kyrolainen et al. 1999)

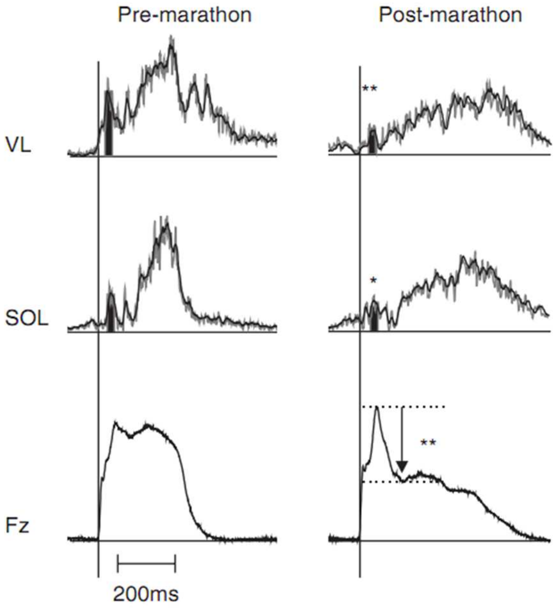


FIGURE 16. Sledge jump performance before and after marathon run. Short latency reflex (Shaded area), EMG-activity and force production decrease after a marathon. (Avela, Kyrolainen et al. 1999)

4.2 Recovery after SSC exercise

Recovery after SSC and concentric exercises is different. SSC performance stays depleted several days after exercise emphasizing that full recovery of muscle structure is crucial to optimal SSC performance (Horita, Komi et al. 2003). In comparison of squat jumps (concentric) and drop jumps (SSC) performance after exhausting SSC exercise the difference is clear. Squat jump performance recovers shortly after exercise, while drop jump performance decreases in following days after exhausting SSC exercise (Horita et al. 2002). Bimodal recovery pattern have been presented after exhausting SSC exercise. MVC recovers quickly (2h) after exercise, but stays depleted for the next 4-8 days. Figure 17 shows a summary of the relative MVC values after exhaustive SSC exercise. However, results may vary depending on parameter. Acute reduction in performance is connected to metabolic fatigue or as normal fatigue. E.g. relative EMG activations are depleted four days after SSC exercise. (Avela, Kyrolainen et al. 1999; Nicol, Avela et al. 2006) Difference in recovery patterns between concentric and SSC induced fatigue proposes that SSC exercise causes more muscle damage and acute metabolic stress. SSC performance is more related to muscle structure, motor command and control strategies. (Horita, Komi et al. 2003) Study of Ishikawa, Dousset et al. (2006) suggested that SSC exercise induced fatigue takes place also in TT – fascicle level. TT is more compliant after exhaustive SSC exercise. More compliant TT can depress performance in MVC situation. Lengths of TT and fascicle did not follow the bimodal recovery pattern. Mechanical behavior of TT - fascicle interaction changed over the recovery period which can have effect to the muscle function. (Ishikawa, Dousset et al. 2006)

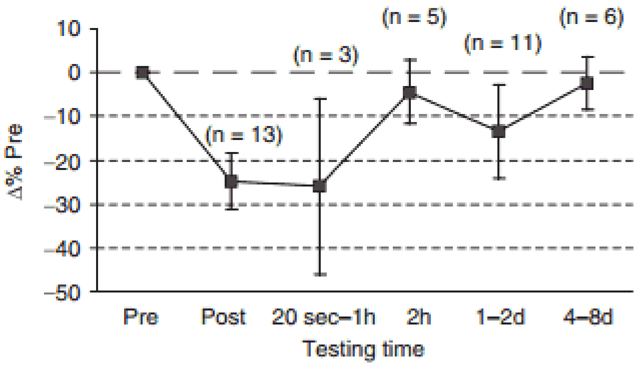


FIGURE 17. Summarized MVC performance data comparing pre values to post exercise values after SSC exercise. (Nicol, Avela et al. 2006)

5 CROSS-COUNTRY SKIING

Cross-country (xc) skiing has come a long journey from way of hunting with self-made wooden skis to competitive sport with hi-tech carbon equipment. Development has had a great effect e.g. to the energy demand of xc-skiing. Formenti, Ardigo et al. (2005) designed a study where replica skies from last 15 centuries were tested in standard conditions. It was found that energy demand of skiing was less than halve (313J/m vs. 140J/m) when oldest replicated skies (542 AD) compared to were compared to modern equipment (2004). During a modern race skiing period from the 70’s to 2004 the change from the solid wood skies to lighter materials has caused great decrease to estimated energy cost of xc-skiing as well (171J/m vs. 140J/m).

Modern xc-skiing include two different techniques classic and skating technique. Both techniques consist of sub techniques. Classical xc-skiing main techniques are double poling, stride double poling and diagonal stride. In skating technique sub techniques are V1, V2 and V2a. V1 is mainly used in uphill’s. V2 and V2a are faster techniques. V2 technique is used in flat terrain or slight up hill. In V2-technigue rhythmic two-sided poling and kicking actions form symmetrical skiing action. In other words one skiing cycle consists of two poling and two kicking action. (Smith 2003 p.50)

5.1 Energy cost of skiing

Utilization of elastic energy in SSC can be estimated as mechanical efficiency of muscle work. Mechanical efficiency in certain task is calculated by dividing produced energy with energy used above resting metabolism. In comparison of pure eccentric and concentric muscle work concentric action consumes less energy. (Abbott, Bigland et al. 1952; Asmussen 1953) Aura and Komi (1986) reported mechanical efficiencies of pure positive work (17.1% +/-2.2%) which is four times lower compared to pure negative work (80.2% +/- 31.8%). Mechanical efficiency of positive work after prestretch is (35.8% +/-6.4%) greatly higher than pure positive work. (Aura and Komi 1986)

Norman and Komi (1987) studied mechanical efficiencies of world class skiers. Result suggested that mechanical efficiency of diagonal level skiing can be as high as 38%. Mechanical efficiency is much higher than earlier estimated under 20% (Niinimaa, Shephard et al. 1979). Mechanical efficiency estimated in level diagonal roller skies show cubic curve for mechanical efficiency as function of speed (figure 18). Estimated mechanical efficiencies are well in line with earlier studies. (Nakai and Ito 2011)

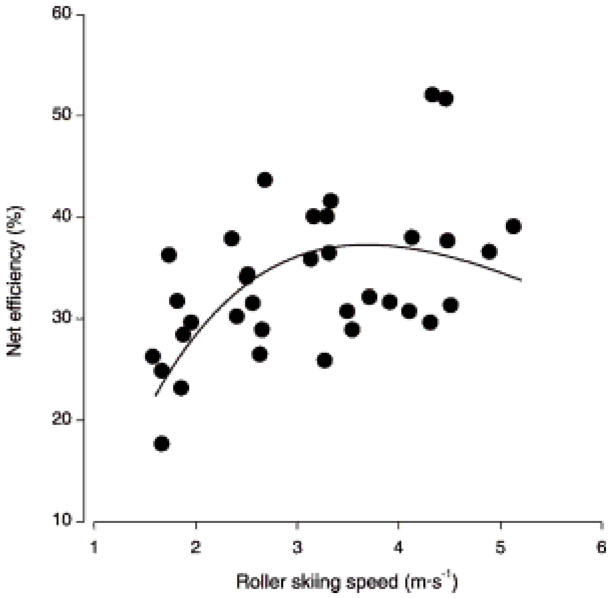


Figure 18 . Mechanical efficiency on level roller skier as function of speed. (Nakai and Ito 2011)

5.2 Speed control in Cross-Country Skiing

Cross-country Skiing is a rhythmic action where repeated cycle can be defined. (Holmberg, Lindinger et al. 2005) Cycle has two main properties: *rate and length.* Speed in cross-country skiing can be defined as a function of these two properties. (Nilsson, Tveit et al. 2004)

Cycle rate have been suggested to increases with increasing speed. E.g. in double poling cycle duration decreases from 2 seconds to 1 seconds from slow to maximum speed. Result is similar in skating techniques where cycle rate is approximately two times faster in high speeds compared to slow speeds. In general cycle rate is slightly slower in skating techniques. (Millet, Hoffman et al. 1998; Nilsson, Tveit et al. 2004) Cycle rate speed ratio varies between different sub-techniques (Hoffman, Clifford et al. 1995).

Cycle length does not have a straight correlation with increasing speed. Cycle length stays close to same while the skiing speed is increased (Nilsson, Tveit et al. 2004) However, in all techniques cycle length can have mild increase from low to medium intensities and mild decreases from medium to high speeds (Hoffman, Clifford et al. 1995; Millet, Hoffman et al. 1998). Cycle length might be influenced by the gliding conditions. Study made in double poling has proposed that cycle length increases with speed. Result can be cause of increased skiing velocities where constant cycle length leads to abnormal cycle rates. (Lindinger, Stoggl et al. 2009)

Performance does not correlate with higher cycle rates. In skiing performance study made in diagonal technique cycle length has a strong correlation with the speed that skier is able to achieve and maintain. (Lindinger, Stoggl et al. 2009) Nilsson, Tveit et al. (2004) concluded that relative phase duration is not changing when skiing speed increases. Moreover, decrease in relative propulsive phase of the cycle in high speeds can also associate to poor technique skills. As a conclusion cycle rate is the main method to increase the speed in xc-skiing but skiers who can maintain cycle length or even increase the length are associated to good performance. Fast and high force production is crucial to competitive skier.

5.3 SSC in xc-skiing

Komi and Norman (1987) studied classical skiing ground forces, EMG and joint angles in diagonal skiing. Based on findings in different of hip, knee and ankle joint usage was concluded that SSC type of movement pattern occurs in hip and knee joints. Hip and knee joints show negative work just before propulsive extension. Figure 19 shows comparison of two (J.L and M.P) skiers. J.L has a clear preloading phase on hip joint where M.P does not.

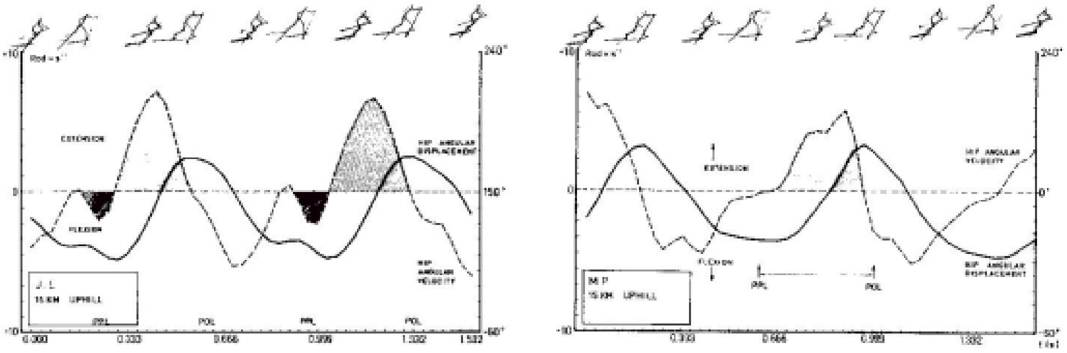


FIGURE 19. Comparison of two elite skier hip angular displacement and velocity curves. Skier J.L have clear preloading phases. (Komi and Norman 1987)

Vähäsöyrinki, Komi et al. (2008) showed the relation between skiing force and muscle activation of diagonal skiing in different skiing speeds. Study was made in Vuokatti on special made force plates where measuring separate forces for poles and skies were possible. Results show a clear preloading activation on of extensor muscles (VL, ES and MG). Activation of each muscle increased with speed. Result is in line with activations showed by Komi and Norman (1987).

Studies made in double poling show that SSC type of movement can be found in upper body muscles in addition to leg and body extensor muscles. Holmberg, Lindinger et al. (2005) showed that in double poling two different strategies can be defined. Difference in strategies is related to angular behavior differences in knee and elbow joints. Strategy involving greater displacement of the mentioned joints showed also higher peak forces as well greater maximal speeds. SSC type of movement pattern is confirmed for elbow and shoulder joint. Increasing speed increases greatly activation in Pma, LD and TRI muscles. Increased peak pole forces can be seen in changed elbow joint movement. Figure 20 shows negative work of elbow after pole plant. (Lindinger, Holmberg et al. 2009) SSC efficiency is estimated by dividing EMG flexion phase activation by extension phase activation. It is also presented that elite skiers are able to increase SSC efficiency with increased speed. (Perrey, Millet et al. 2000; Zoppirolli, Holmberg et al. 2013)

SSC has been studied in skating xc-skiing. SSC type of movement pattern has been identified in all skating techniques from lower limb muscles. Moreover it was suggested that skating techniques used in flat terrain (V2 and V2a) are more favorable to SSC.

(Candau, Belli et al. 1994; Perrey, Millet et al. 1998) V2a skating technique has been studied roller ski skates as function of speed. EMG measurements were taken from VL and GL muscles. Result suggests that maximal speeds are achieved by greater stretching velocity of GL muscle. (Perrey, Millet et al. 2000)

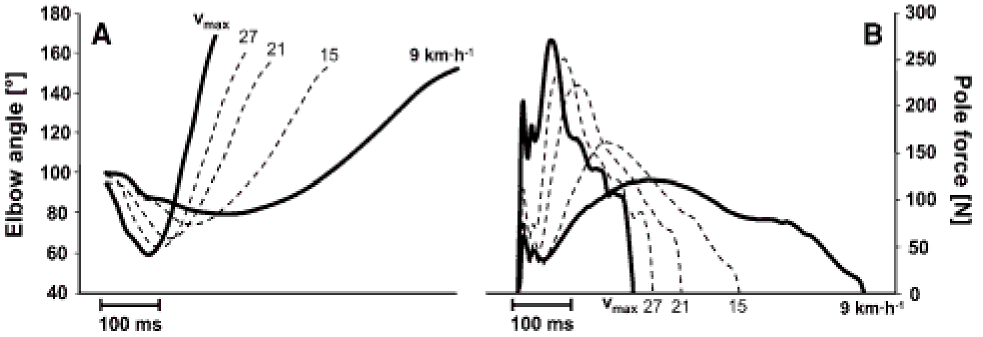


FIGURE 20. Change in elbow angle and pole force with increasing speed. (Lindinger, Holmberg et al. 2009)

So far only one study has examined muscle tendon behavior in diagonal cross country skiing using US. Measurements have been carried out in Vuokatti ski tunnel. Skier carried US measurement device weighting 5kg. Trials carried out in slight uphill 2,5 % with 4.5 m/s speed. Muscles are stretched in eccentric phase and shortened in concentric phase. Furthermore MTU behavior was more uniform to what were expected (figure 21). (Ishikawa, Sano et al. 2010)

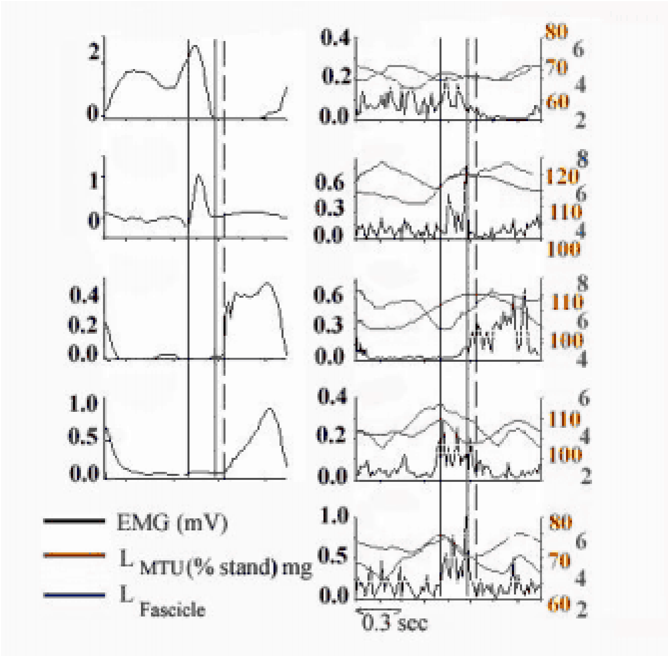


FIGURE 21. Unique records combining force (Fz and Fy) measurements to EMG, Fascicle and MTU lengths of VL, RF, TB, MG and SOL during diagonal skiing. (Ishikawa, Sano et al. 2010)

5.4 Fatigue in xc skiing

SSC type of movement pattern has its time and place in xc-skiing meaning that SSC type of fatigue can be found in fatigue studies after xc-skiing. Furthermore fatigue induced by xc-skiing is different than in well studied exercise like running because of its anti-shock nature causing less muscle stress i.e. central fatigue after has been confirmed after prolonged running but not after xc-skiing or cycling. (Millet and Lepers 2004) Xc-skiing fatigue induces loss of muscle strength in knee extensors. In a study made of marathon skiing it was concluded that long duration exercise caused loss in muscle strength but also potentiation in nervous system (Millet, Martin et al. 2003). Moreover, fatigue is reported to exist in both upper and lower body muscles (Zory, Millet et al. 2006; Zory, Vuillerme et al. 2009). In comparison of xc-skiing race to marathon run race as same duration causes less muscle damage and power loss. (Takashima, Ishii et al. 2007)

The effect of fatigue in double poling biomechanics has been covered with several studies in sprint xc-skiing. In sprint xc-skiing it is crucial to maintain ability to achieve maximal speed at the end sprint. Performance lost in snow sprint skiing simulation is related to increase in poling phase duration without change in poling lengths. Moreover, fatigue is reported to reduce angular levels of hip joint. EMG activation patterns do not change between first and last heats in double poling sprint skiing. However, signs of the fatigue exist right after first heat especially in upper body muscles (Zory, Vuillerme et al. 2009; Zory, Molinari et al. 2011). Spurting ability has been reported to decrease within the sprint skiing heats. However, Spurting ability recovers well between heats (Vesterinen, Mikkola et al. 2009; Mikkola, Laaksonen et al. 2013). Vesterinen, Mikkola et al. (2009) highlighted the importance of the recovery time between heats in sprint skiing. On a study made in indoor track with the roller skies in V2 technique decrease in performance was reported during the heat, but the study suggested that 20–min recovery is enough to recover between the heats. However, study is in contrast with the study of Mikkola, Laaksonen et al. (2013) which suggest accumulation of the fatigue between heats.

Decreased performance is associated to the decrease in poling force, reduction in cycle length and increase in cycle frequency (e.g. Zory, Millet et al. 2006; Vesterinen, Mikkola et al. 2009; Mikkola, Laaksonen et al. 2013; Zoppirolli 2013). Furthermore, high–level skiers are associated to the ability to maintain they own technique in fatigued situation. Moreover, Zoppirolli (2013 p. 73-77) emphasized the importance of the body inclination in the early poling phase, suggesting that fatigue can lead to lower body inclination causing reduction in the peak pole forces and cycle duration. (Zoppirolli 2013 p. 73-77).

6 PURPOSE OF STUDY

Stretch shortening cycle (SSC) is natural way to increase performance in ex. running. (Kyrolainen, Avela et al. 2005) US measurements give a closer view to how SSC is utilized in muscle tendon unit level (MTU). SSC occurrence is confirmed in xc-skiing in both upper and lower body muscles. Norman, Linnamo et al. (2010) have given the tools to coaches to teach how to utilize SSC in xc-skiing. One unique study is done in Vuokatti which provides the MTU information in classical xc-skiing (Ishikawa, Sano et al. 2010). However there are no studies showing MTU behavior in muscle fascicle level in skate xc-skiing.

Purpose of the study was to provide data of MTU behavior during skate V2 xc-skiing by providing TT – fascicle behavior measurements for vastus lateralis (VL), medial gastrocnemius (MG), triceps brachii (long head) (TRI) and rectus femoris (RF) muscles in vivo V2 skate technique. Ultrasound measurements were combined to the EMG and kinematic data measurements. Study was done in normal and fatigued conditions. Fatiguing exercise was 20 km simulated skiing race. Both conditions consisted of trials with several velocities. Velocities were selected to demonstrate training, racing and maximal speeds.

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CONTENT OF THE ARTICLE

1 INTRODUCTION

Cross-country (xc) skiing has been a transportation method in the artic areas for over a thousand year. Over the time xc-skiing has been developed to a competitive sport as we know it nowadays. Xc-skiing is a complex sport containing lot of changing variables. Skiing is generally divided in two different techniques which both has several sub-techniques. Races are mainly carried out in outdoors where condition changes have great influence e.g. to the sliding properties of the ski. Tracks are often done in variable terrain requiring continuous variation in the used technique. (Ohtonen, Lindinger et al. 2013)

Development of equipment and track preparation has enabled the development in skiing velocities. Stiffer and lighter equipment and better prepared tracks allow greater force production. Together with changes in racing modes towards sprint skiing and mass start races changes have made sprinting ability and economy in force production crucial to competitive xc-skiers. (see refs. Holmberg, Lindinger et al. 2005)

V2 skate xc-skiing is sub-technique of skate xc-skiing technique which is widely used in modern xc-skiing. In V2-technigue rhythmic two-sided poling and kicking actions form symmetrical skiing action. In other words on skiing cycle consist of two poling and two kicking action. (Smith 2003 p. 50) As a locomotion skate xc-skiing is different from the nature compared to most common locomotion like walking and running or even diagonal xc-skiing. In skate xc-skiing leg ground contact does not have clear braking phase because the force is produced to a moving base.

Stretch shortening cycle (SSC) is a movement pattern where activated muscle is stretched before shortening. SSC is natural strategy to muscle tendon unit (MTU) to produce more force or produce submaximal force more economically. Human performances like running and hopping where external forces cause muscle stretch are favorable to SSC to occur. SSC loads neuromuscular system more sophisticated than pure concentric action. In SSC energy is stored in elastic component of the muscle. Stored energy is restored during the concentric phase of the movement. Muscle action can be enhanced and regulated by the reflexes during SSC movement pattern. Short latency reflex occurs after ground contact. Preactivity plays a role in reflex sensitivity and regulation the actions before voluntary control. (Komi 2000)

Komi and Norman (1987) first presented the use of SSC in xc-skiing. Komi estimated that mechanical efficiency of diagonal xc-skiing can be as high as 38% because of efficient use of SSC. Estimated efficiency is much higher than in pure concentric work (Aura and Komi 1986). SSC use of lover limb muscle has been confirmed in classical and skate xc-skiing techniques (Komi and Norman 1987; Candau, Belli et al. 1994; Perrey, Millet et al. 2000). Double poling studies have confirmed SSC use in upper body muscles (Holmberg, Lindinger et al. 2005; Lindinger, Holmberg et al. 2009). Effect of speed to utilization of SSC has been studied by comparing activation levels in eccentric and concentric phases during ground contact showing that utilization of SSC increases with speed (Kyrolainen, Avela et al. 2005; Lindinger, Holmberg et al. 2009). Moreover it is suggested that elite xc-skiers can increase efficiency of SSC with increasing speeds. (Perrey, Millet et al. 2000; Zoppirolli, Holmberg et al. 2013).

Ultrasonography (US) is a noninvasive method to study muscle tendon unit (MTU) behavior in locomotion. US measurements enable to observe muscle fascicle behavior in vivo and estimate the muscle MTU elastic and contractile component behavior (Fukunaga, Ichinose et al. 1997). Muscle tendon unit (MTU) consists of tendinous tissue (TT) and contractile component (fascicle). TT-fascicle interaction is impossible to predict in different locomotion. MTU behavior is muscle task dependent and can change in different intensities in the same task. (Ishikawa 2005)

Locomotion is widely studied in MTU level (ex. Fukunaga, Kawakami et al. 2002). However there is a lack of studies of MTU behavior in xc-skiing. One unique study has been done in Vuokatti about MTU behavior in diagonal xc-skiing in different speeds. Study confirms SSC type of movement pattern of MTU in skiing. (Ishikawa, Sano et al. 2010) No study has been done to analyze MTU behavior in skate xc-skiing.

Fatigue of neuromuscular system can be divided into central fatigue or peripheral fatigue. Central fatigue refers to a spinal and supraspinal mechanisms. Peripheral fatigue consists of deterioration in excitation-contraction coupling in muscular level. Furthermore muscle potentiation can enhance neuromuscular output during performance. (Enoka 2002, p.317-342) Long lasting submaximal SSC exercises like marathon run cause both central and peripheral fatigue. It is suggested that anti-shock nature of xc-skiing changes the origin of fatigue if compared to running. Xc-skiing causes little or no central fatigue and performance deterioration is related to peripheral fatigue. (Millet, Martin et al. 2003; Zory, Millet et al. 2006) Furthermore it has been reported that long lasting SSC exercise can increase tendon compliance in TT – fascicle level (Avela, Kyrolainen et al. 1999). No TT - fascicle level studies have been done in fatigue in xc-skiing.

General purpose of current study was to continue measurements related to the SSC and cx-skiing in Jyväskylä University and to provide first TT – fascicle level pilot data in V2 skate xc-skiing. One similar study providing the data in TT – fascicle level has been done in diagonal xc – skiing in Jyväskylä University (Ishikawa, Sano et al. 2010).

Aim of the study is to provide unique TT – fascicle level data during V2 skate xc -skiing and provide notes for the further measurements. Main questions for the study are: (1) can muscles be stretched during V2 xc-skiing ground contact? (2) Can use of elastic component be strategy to enhance muscle performance? (3) How fatigue changes the TT – fascicle behavior? Vastus lateralis (VL), medial gastrocnemius (MG), triceps brachii (long head) (TRI) and rectus femoris (RF) MTU behavior was measured in TT – fascicle level during *in vivo* V2 skate xc-skiing. Study was carried out in three different velocities in non-fatigued situation and in two different velocities in fatigued situation. In addition to the ultrasound measurements EMG and force measurements were carried out.

2 METHODS

2.1 Subject

In this study, one experienced skier (182cm, 85kg) was selected to perform all trials. Protocol was trained several times before measurements. Subject was familiarized for skiing with the measurement systems (figure 1). Carefully performed familiarization was essential to minimize the influence of measurement system weight (13.2kg).

2.2 Measurement protocol

Measurements were carried out in stable conditions in Vuokatti ski tunnel. Trial sets were performed in slight uphill (4%). Trial area was 50m long. Area consisted of acceleration area of 20m and measurement area of 30m. Measurement area for kinematic data was 18m and located at the end of the measurement area.

Measurements consisted of two trial sets. Pre measurement (non-fatigue) consisted of 12 trials. Trials were carried out in three velocities (SLO; 4m/s, MED; 6m/s and MAX). Before pre measurements subject performed a 15 min warm up. Between trial sets subject carried out 20km race simulation in the ski tunnel. Separate skies were used during the race simulation to avoid changes in gliding properties of the skies. Post measurements (fatigued) consisted of 8 measurements where velocities (MED (6m/s) and MAX)) were used.

FIGURE 1. Measurement setup. Infrared cameras were attached to the rail in the tunnel. Measurement setup (13.2kg) was carried in rucksack.

Four muscles were selected for the EMG and US measurements: vastus lateralis (VL), medial gastrocnemius (MG), triceps brachii (long head) (TRI) and rectus femoris (RF). Measurements were performed separately to each muscle in different speeds. After measuring the one muscle with all speeds probe was changed to the next muscle. Speed was controlled with visual pacemaker (Naakka Oy, Lappeenranta Finland). Recovery time between trails was standardized to 3min.

2.3 EMG and Force measurements

EMG was recorded (1000Hz) from each muscle in all measured muscles in every trial. (Noraxon, Scottsdale, USA). Electrodes were placed on the side of the probe in direction according to muscle fibers. EMG recordings were band pass filtered (10 – 499 MHz) and rectified before analyze.

For the leg muscle ground contact time was divided into 5 phases according to the eccentric and concentric phases of the each muscle MTU (figure 2); PA = preactivity

(100ms before ground contact), EX1=eccentric phase 1, CO1=Concentric phase 1, EX2=eccentric phase 2 and CO2=Concentric phase 2 (picture 2). TRI muscle ground contact was divided into 3 phases: PA = preactivity (100ms before ground contact), EX=eccentric phase, CO=Concentric phase. Average EMG (aEMG) was calculated to each phase. Only the cycles (one per trial) where US measurement was carried out were analyzed.

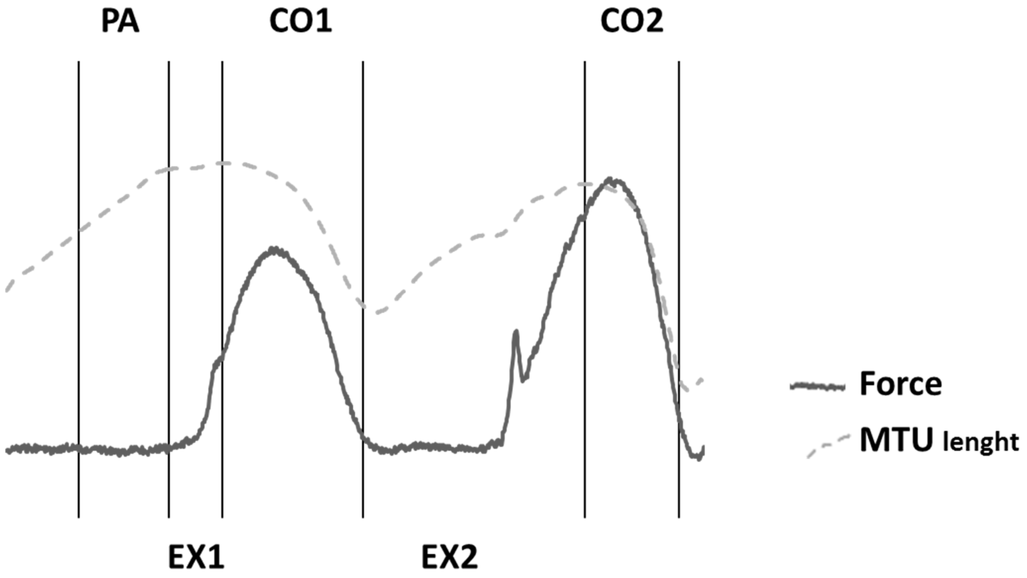

FIGURE 2. Example data including leg force (solid line) and VL Length$_{MTU}$ (dotted line) during on cycle. In the leg muscle EMG analyze, ground contact time were divided to 5 phases (PA = preactivity (100ms), EX1=eccentric phase 1, CO1=Concentric phase 1, EX2=eccentric phase 2 and CO2=Concentric phase 2) respect to muscle tendon unit lengthening direction.

Axial pole forces (VELOMAT, Germany) were recorded (1000Hz) from the right pole. Leg forces were recorded (1000Hz) from the right ski with special made force binding (Ohtonen, Lindinger et al. 2013). Binding measured vertical and cross directional force from the ski. Forces under the heel and the ball of the foot were measured separately. Skier's velocity was measured with radar (Jenoptic LDM 300 C SPORT, Jena Germany)

Analysis for the force data was done only on cycles where US data was analyzed (one per trial). Variables were averaged according to trial speed to estimate uniformity of analyzed cycles. Variables were analyzed from the right ski and right pole forces. From leg force data times for cycle time (CT), ground contact (GCT), Unloading phase (UPH), time to peak forces 1 (TPF1) and 2 (TPF2) were analyzed. Corresponding variables were analyzed from pole forces: Pole Cycle Time (CT_{pole}) Poling time (PT), and Time to Peak Force ($TTPF_{pole}$). Maximal forces were analyzed for leg and pole forces (MF1, MF2 andPF_{pole}). Leg force curve consist of two peaks during ground contact and both forces were analyzed separately. From the times and forces Rate of Force Development (RFD and RFP_{pole}) were calculated. (figure 3)

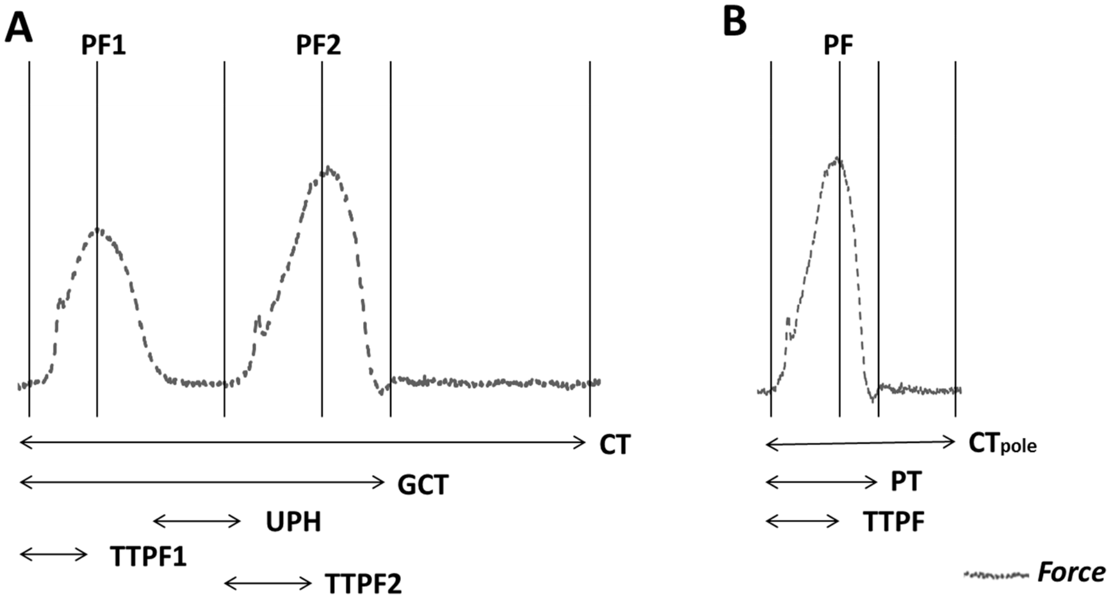

FIGURE 3. A: ski and B: pole force (dotted line) from one full cycle. From the leg forces cycle time (CT), Ground Contact Time (GCT), Unloading Phase Time (UPH), Time to Peak Force 1 (TPF1), Time to Peak Force 2 (TPF2), Maximal Force 1, Maximal Force 2 and Rate of Force Development (RFD) were analyzed. From pole data corresponding variables are: Cycle Time Pole (CT_{pole}), Poling time (PT), Time to Peak Force ($TTPF_{pole}$), Peak Pole Force (PF_{pole}) and Rate of Force Development (RFP_{pole}).

2.4 Muscle Tendon Unit behavior

2.4.1 Joint angle measurements

Motion data was measured with 3D motion capturing system (Vicon, Oxford, UK). Infrared cameras were placed beside the measurement area. Eight reflecting makers were used to describe desired angles. Marker set were reduced from the set introduced in Vicon manual. Markers were located in: (1) right shoulder, (2) right elbow, (3) upper right wrist, (4) right hip front, (5) right knee, (6) right ankle and (7) right toe.

MTU length ($\text{Length}_{\text{MTU}}$) for leg muscles (VL, MG and RF) were calculated from angle data according to study of Hawkins and Hull (1990). Length for TB muscle MTU was estimated using Stanford VA upper limb model (Holzbaur, Murray et al. 2005). Model was run in OpenSim v.3.2. software (Delp, Anderson et al. 2007).

2.4.2 Muscle tendon measurements

Ultrasound was recorded (72.4 Hz) with portable US system (Prosound C3cv, Aloka Japan). During the trials US device (weight 10.2kg) were carried by the subject in a rucksack. (figure 1) Simulated skiing race was performed with the rucksack without US recording system to not disturb the marker placement. Two similar probes (width 4 cm, measurement depth 3cm) were used in US recordings. However one muscle (all speeds) was recorded at the set due the limitation of the measurement system. Use of two probes eased the preparation and enabled the measurement to be carried out faster. Probes were attached firmly to the muscle belly before each trail set. (picture 4)

PICTURE 4. Attached probes for the MG and VL measurements. Ultrasound probes were firmly attached over the muscle belly.

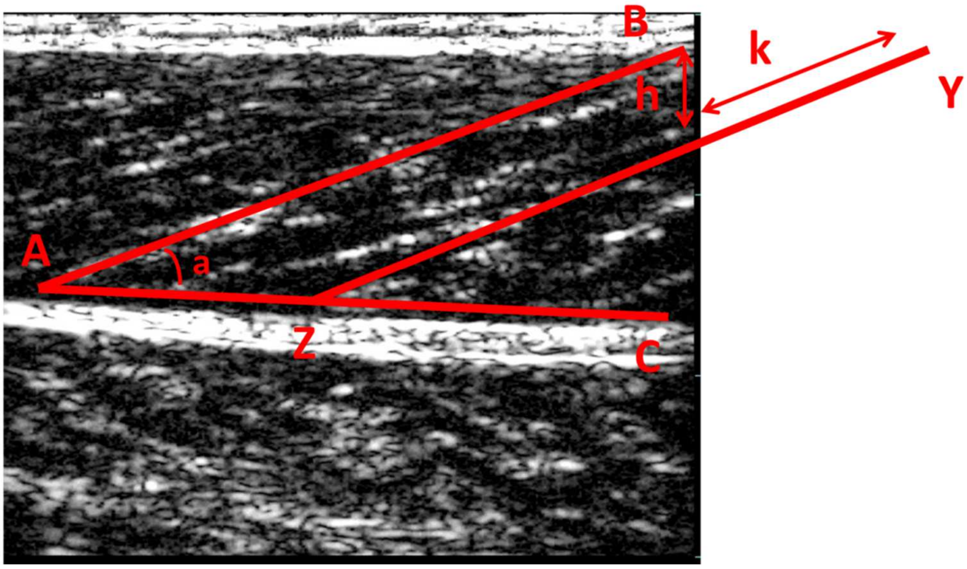

FIGURE 5. Fascicle length and pennation angle measurements from MG muscle. Fascicle length A to B and angle A between B and C were analyzed manually from the US sonograms. In case fiber did not fit to a sonogram (Z to Y) length of k was estimated using the length h.

Ultrasound measurements was analyzed manually. Manual analysis consisted of three points (A = muscle fiber attachment point to inner aponeurosis, B= Muscle attachment point to superficial aponeurosis and C= reference point from inner aponeurosis). Muscle fiber length was defined as distance between points A and B. Pennation angle (a) was measured between B to C where A was the center point. In case that whole muscle fiber did not fit to the sonogram, length of the fiber was estimated by adding estimated length of the remaining fiber to the measured fiber length. (figure 5) (Ishikawa 2005 p. 38-40) Equation 1 was used the estimate total fiber length.

$$Fiber\ length = measured\ length + h / \sin a \quad (1)\ (figure\ 5)$$

Muscle fiber length (Lenght$_{Fiber}$) and angle (Angle$_{Fiber}$) data was combined to MTU data and used to calculate Tendinous Tissue Length (Length$_{TT}$) (Fukunaga, Kubo et al. 2001) (picture 6). Length$_{TT}$ was calculated according to Equation 2.

$$Length_{TT} = Length_{MTU} - Length_{Fascicle} \times \cos Angle_{Fascicle} \quad (2)$$

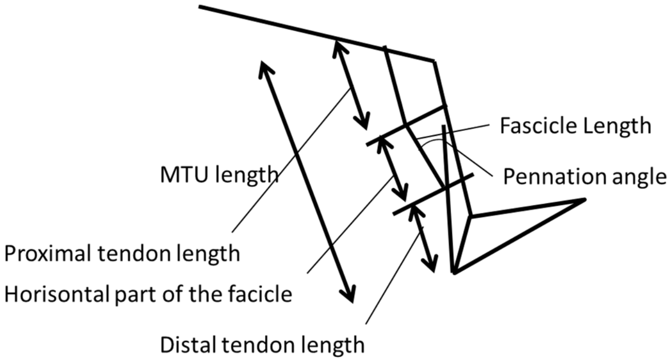

FIGURE 6. Medial gastrocnemius MTU model used to calculate tendinous tissue (TT) length. Fascicle length and pennation angle is estimated from ultrasonograms. MTU length is estimated from joint angles using a model. MTU model Adopted from Fukunaga, Kubo et al. (2001) .

2.5 Data processing and Statistical analyses

EMG and force data were processed in IKE-master v. 1.38 (IKE Software Solutions, Salzburg). Manually analyzed US data was processed with Excel 2010 software

(Microsoft Corp. Redmond, USA). Marker locations in 3D space where exported from Vicon Nexus 1.7.1 software (Vicon, Oxford, UK) Angle data (elbow-, hip- , knee- and ankle angle) were calculated in Excel 2010 software (Microsoft Corp. Redmond, USA). Final data sets were combined to the force data and analyzed in IKE-master v. 1.38 (IKE Software Solutions, Salzburg).

Similarity of variables in between different velocities and conditions were compared by calculating relative standard deviation (RSD) in addition to standard deviation (SD). Changes were compared as percentage differences between variables. No statistical analyses were done due the small subject group and an experimental nature of the study.

3 RESULTS

3.1 Force measurements

Uniformity of the trials varies according to used variable. Biggest relative standard deviation (RSD) values were found in UPH (4.1% - 21.7%), TPF1 (5.9%-15.2%) and RFD (6.9% - 16.5%). However variables such as speed (0.9% - 4.2%), GCT (3.0%-4.7%), MF (2.6%-10.2%) were more uniform. In terms of average RDS POST condition trails were slightly more uniform compare to PRE trails (8.0% vs. 5.7%).

Between PRE (non-fatigued) and POST (fatigued) conditions biggest shifts were in variable such a UPH (MAX: -20.3% MED: 13.8%), TPF1 (MAX: -8.6% MED: 14.3%), MF1 (MAX: -9.0% MED 11.8%) and RFD (MAX -8.8 MED: 9.0%). Subject was able to keep the desirable velocity in PRE and POST MED speed trials (-1.3%). Difference between MAX velocities difference was smaller (-0.6%) than in MED condition.

In PRE condition MED velocity RDF is 213% of RFD in SLO condition. Respectively in MAX condition RFD was 191% higher compared to MED condition. In fatigue situation MAX velocity RDF was 160% of MED RFD. CT was 20% shorten in MED condition compared to SLO and 13% shorten in MAX compared to MED. CL was highest in MED velocities. CL decreased 7% in PRE and 9% in POST condition in MAX velocity compared to MED velocity.

TABLE 1. Difference between analyzed variables in PRE and POST conditions. POST Pole analyses are missing due the breakdown of the pole force sensor. Calculation of standard deviation for pole variables was unreasonable due small sample count.

	PRE						**POST**			
	MAX	**std**	**MED**	**std**	**SLO**	**std**	**MAX**	**std**	**MED**	**std**
SPEED (m/s)	6,15	0,09	5,76	0,14	3,86	0,11	6,11	0,05	5,69	0,24
CT (s)	1,29	0,01	1,48	0,03	1,86	0,05	1,28	0,02	1,51	0,05
GCT (s)	0,78	0,03	0,87	0,03	1,12	0,03	0,78	0,02	0,93	0,04
UPH (s)	0,19	0,01	0,11	0,02	0,14	0,02	0,15	0,01	0,13	0,01
TPF1 (s)	0,14	0,02	0,15	0,01	0,20	0,04	0,13	0,01	0,17	0,02
TPF2 (s)	0,18	0,03	0,28	0,02	0,35	0,03	0,19	0,00	0,28	0,02
MF1 (N)	1469,78	53,48	1136,97	173,20	1079,74	64,72	1348,37	118,06	1289,19	61,08
MF2 (N)	1935,40	97,73	1739,25	176,82	1452,04	38,07	1952,71	98,07	1774,72	71,45
RFD (N/s)	11085,60	1816,85	5793,64	541,94	2724,36	429,03	10184,98	703,96	6366,50	592,41
CT_{pole} (s)	0,64		0,74		0,90					
PT (s)	0,24		0,29		0,37					
TTPFpole (s)	0,09		0,15		0,23					
PFpole (N)	365,00		230,30		187,60					
RFDpole (N/s)	3882,98		1566,67		833,78					

Leg forces cycle time (CT), Ground Contact Time (GCT), Unloading Phase Time (UPH), Time to Peak Force 1 (TPF1), Time to Peak Force 2 (TPF2), Maximal Force 1, Maximal Force 2 and Rate of Force Development (RFD) were analyzed. From pole data corresponding variables are: Pole Cycle time (CL_{pole}), Polling time (PT), Time to Peak Force ($TTPF_{pole}$), Peak Pole Force (PF_{pole}) and Rate of Force Development (RFP_{pole}).

MF2 values were very close the same in PRE and POST situations (MAX 0.89% MED 2.00%). Biggest difference between PRE and POST conditions forces were found in MF1. MF1 shifted down in MAX (-9.00%) situation and respectively up in MED (11.81%) situation in POST condition. (figure 7)

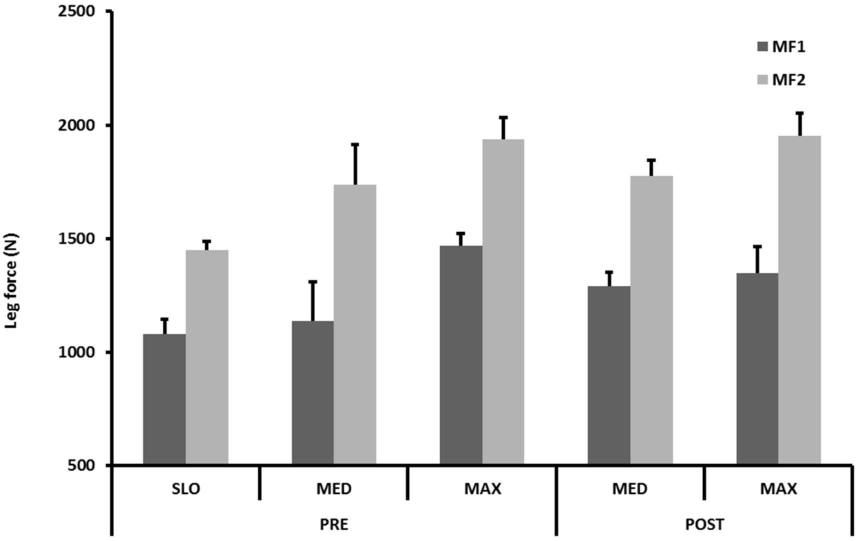

FIGURE 7. Average maximal forces with standard deviation from PRE and POST conditions. MF1 and MF2 are leg maximal force peaks near first and second force peak during ground contact.

3.2 EMG analysis

Phase pattern did not change between PRE and POST condition. MG and VL POST preactivation aEMG levels were lower (MAX: 30% and MED: 69%) than in PRE condition. VL aEMG in POST condition EX1 drops 37% compared to PRE condition. (figure 8a and 8b)

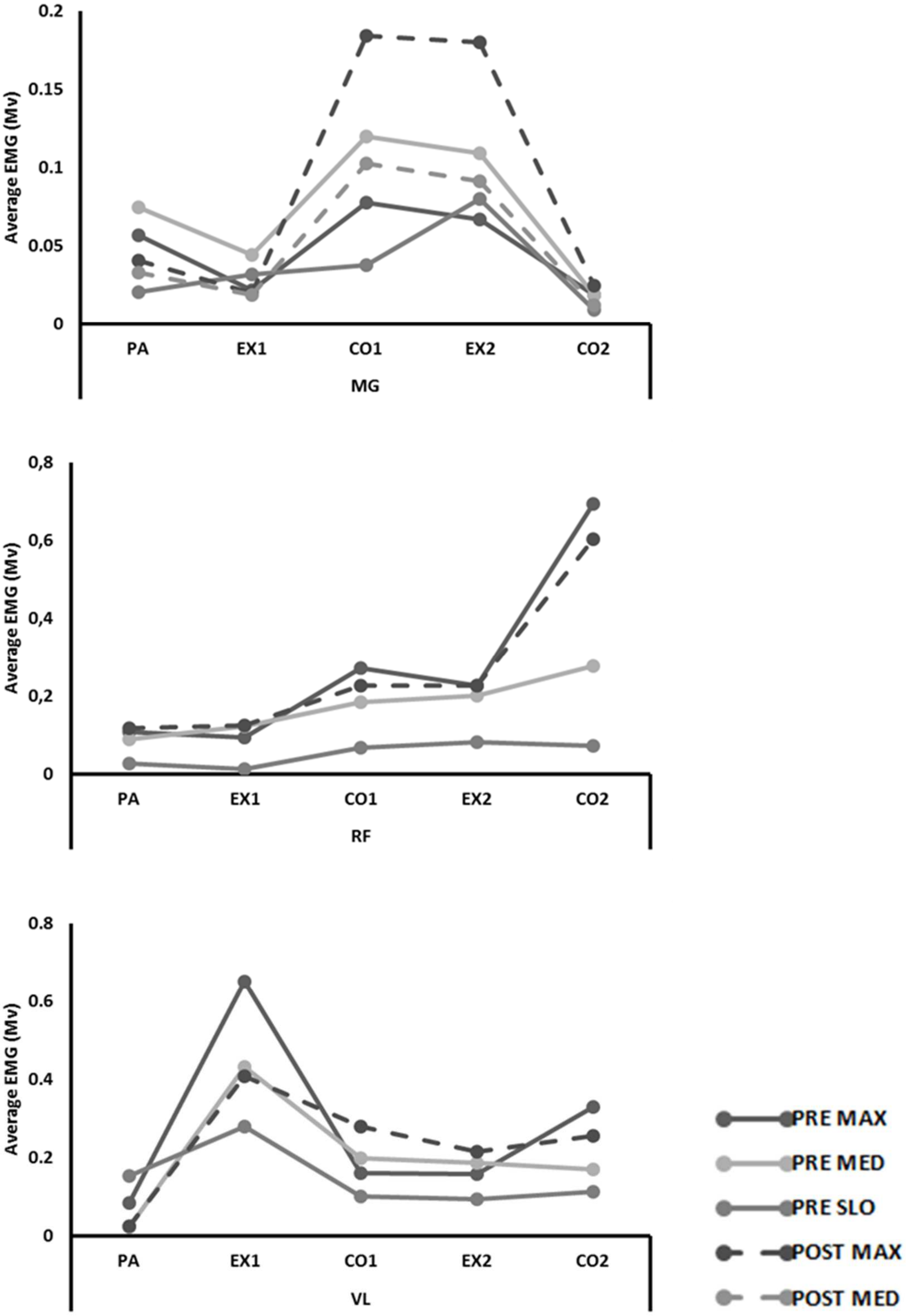

FIGURE 8a. EMG analysis of the leg muscles. MG, RF and VL muscles show SSC type of activation pattern where activation in eccentric phase is greater than following concentric phase. **POST MED RF and VL and POST aEMG values could not be analyzed due measurement problems.

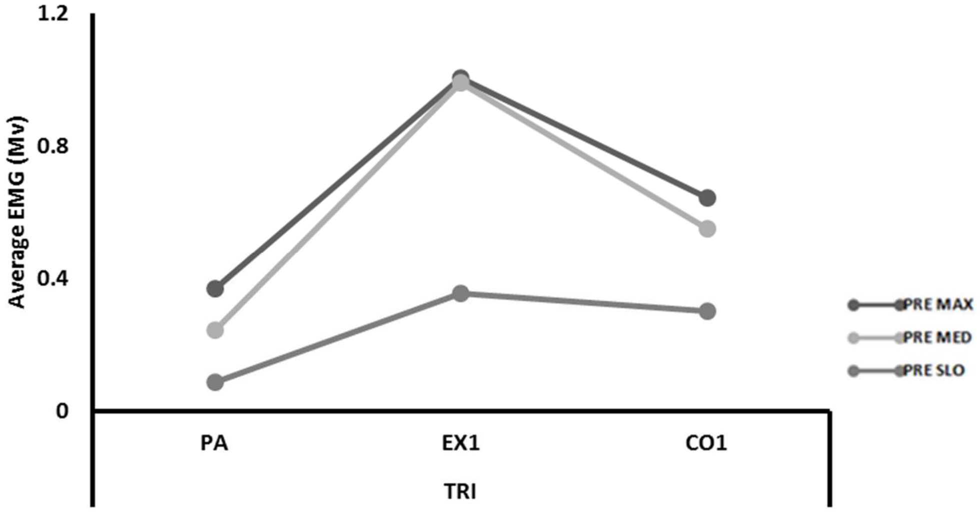

FIGURE 8b. EMG analysis of TRI muscle. TRI muscle shows SSC type of activation pattern where activation in eccentric phase is greater than following concentric phase. **POST MED TRI aEMG value could not be analyzed due measurement problems.

3.3 TT – fascicle behavior

Only visual inspection has been done to the data. Numeral analyzing was impossible to perform because of the high sensibility of analyze. Due the low sample size any averaging could not be carried out. However, VL (figure 9) and TRI (figure 12) muscles showed more stretch in TT with increasing speed. Biarticular muscles MG (figure 10) and RF (figure 11) showed stretch in TT during contact phase, but did not show clear change in TT behavior with increasing velocity. However, MG fascicle behavior changed respect to the velocity. Fatigue did not change the behavior of the measured muscles.

3.3.1 Vastus Lateralis (VL)

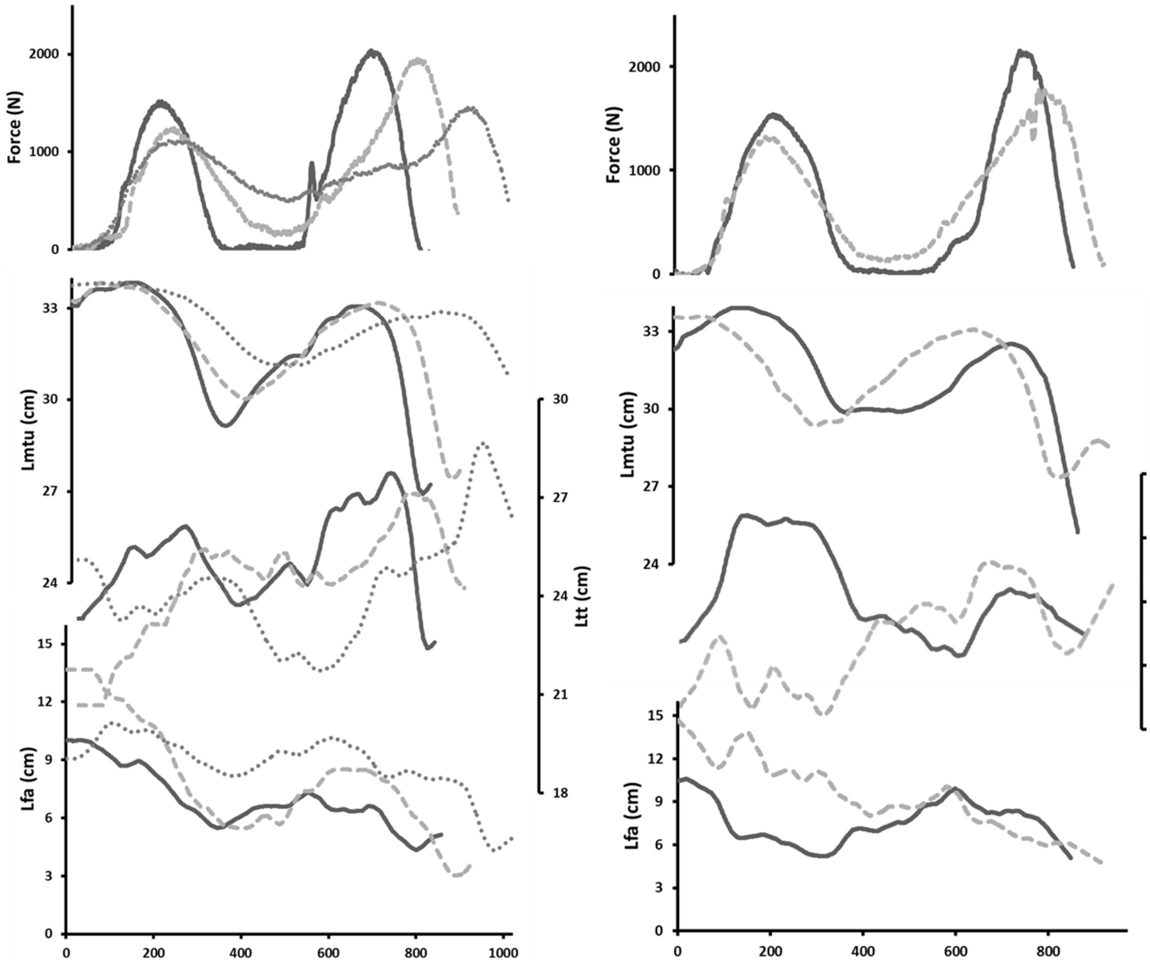

FIGURE 9. Length$_{MTU}$, Length$_{Fa}$ and Length$_{TT}$ of Vastus Lateralis (VL) muscle in non-fatigued (A) and fatigued (B) condition in different speeds (solid line = MAX, dashed line = MED and dotted line = SLO). ** POST MED not synced due missing trigger file.

3.3.2 Medial Gastrocnemius (MG)

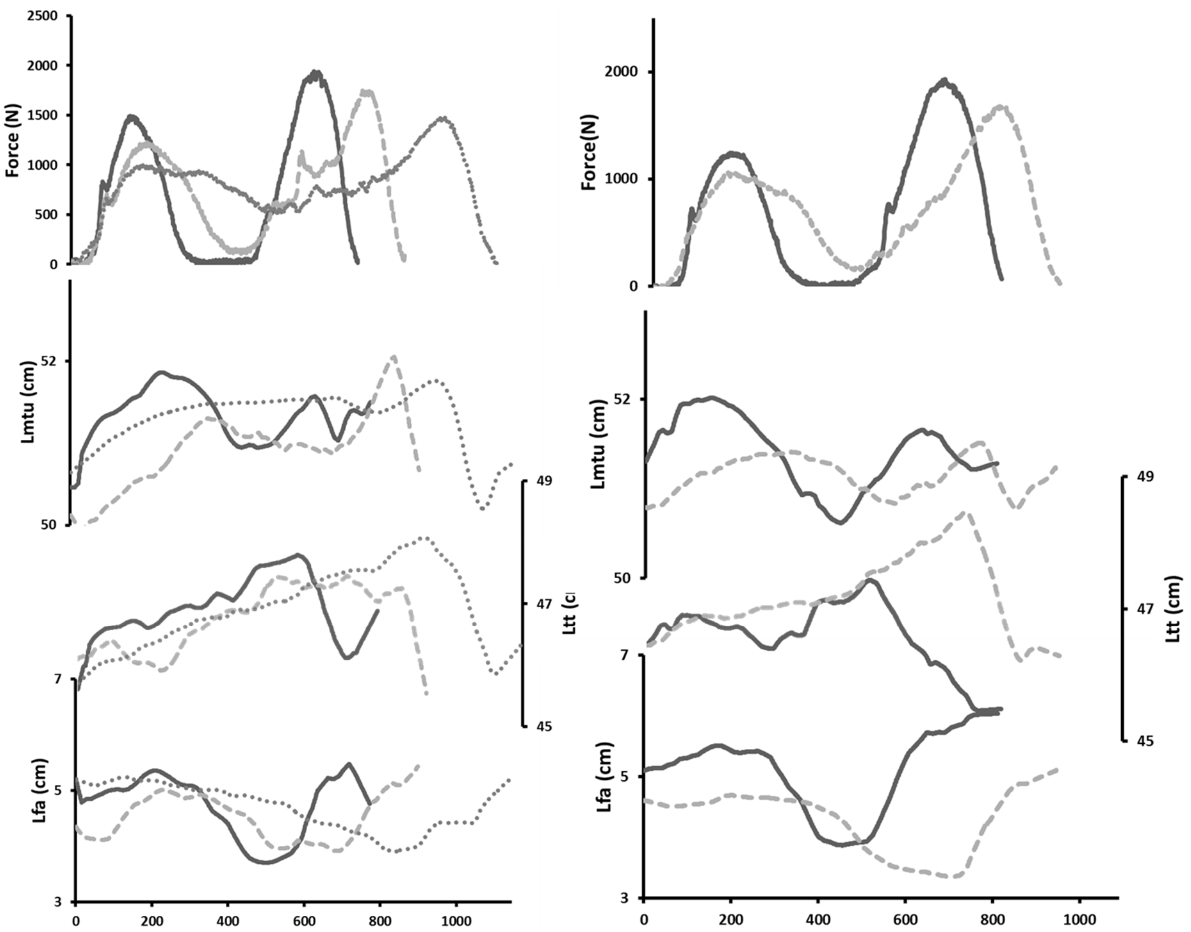

FIGURE 10. Length$_{MTU}$, Length$_{Fa}$ and Length$_{TT}$ of Medial Gastrocnemius (MG) muscle in non-fatigued (A) and fatigued (B) condition in different speeds (solid line = MAX, dashed line = MED and dotted line = SLO).

3.3.3 Rectus Femoris (RF)

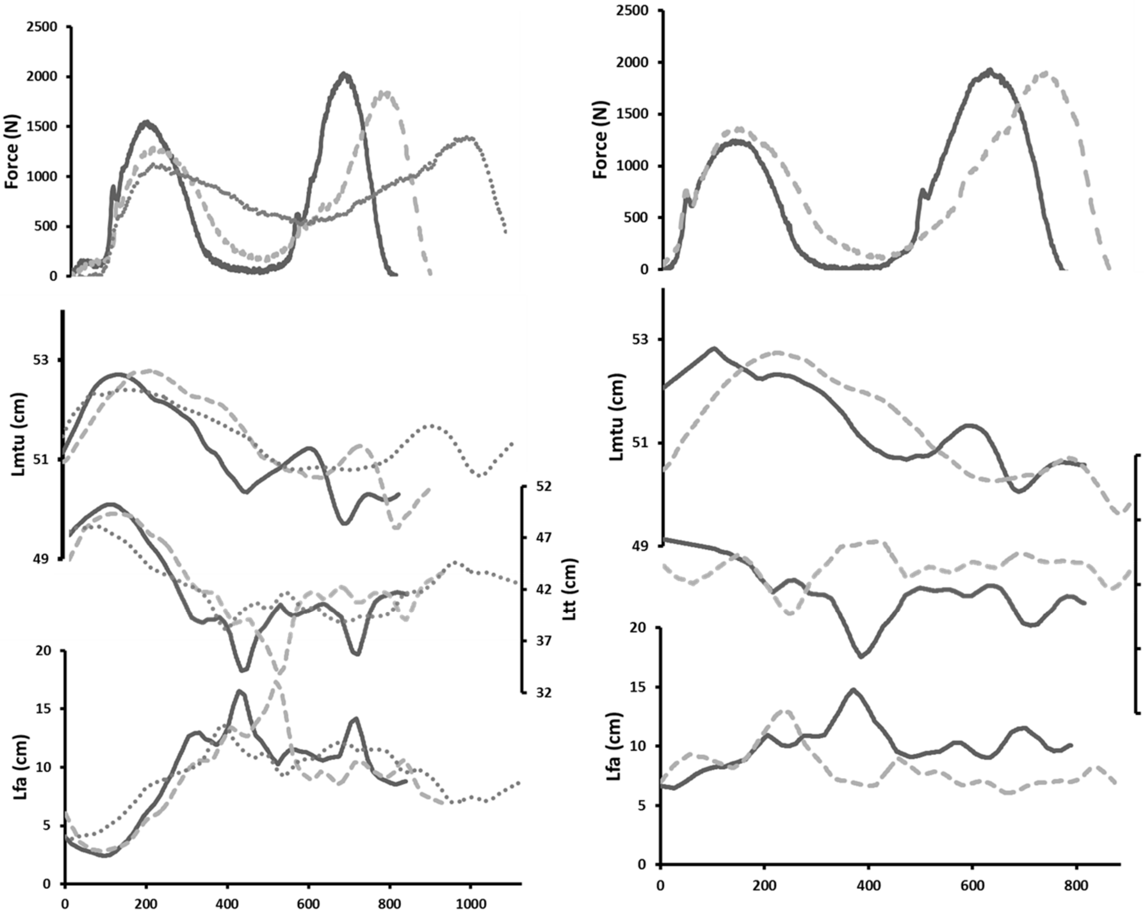

FIGURE 11. Length$_{MTU}$, Length$_{Fa}$ and Length$_{TT}$ of Rectus Femoris (RF) muscle in fatigued (A) and fatigued (B) condition in different speeds (solid line = MAX, dashed line = MED and dotted line = SLO).

3.3.4 Triceps Brachii (long head) (TRI)

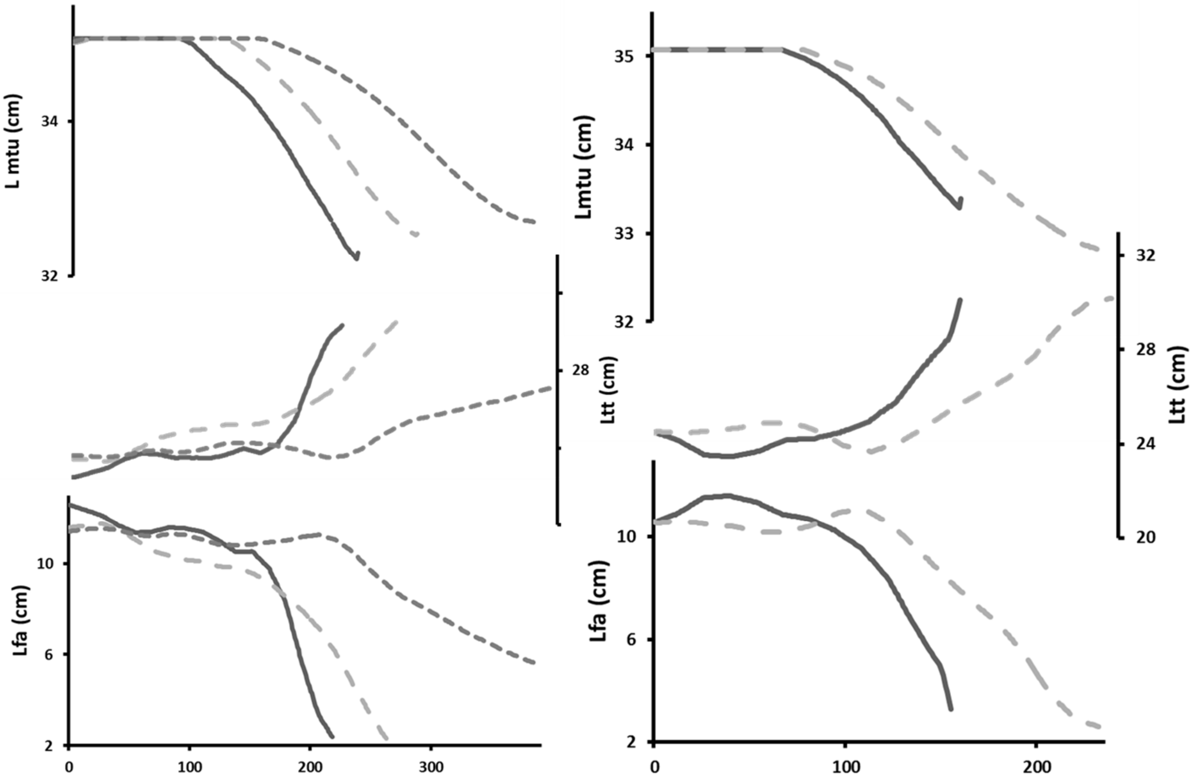

FIGURE 12. Length$_{MTU}$, Length$_{Fa}$ and Length$_{TT}$ of Triceps Brachii (long head) (TRI) muscle in fatigued (A) and fatigued (B) condition in different speeds (solid line = MAX, dashed line = MED and dotted line = SLO). **Illustrative purpose only due the limitations of the used model and measurement problems.

4 DISCUSSION

This study is highly experimental and serves only as a pilot study. However, data suggest that (1) studied leg muscles and TRI muscle show stretch of TT during V2 skate xc-skiing ground contact phase, (2) VL and TRI muscle show increase in stretch with increasing velocity, (3) TT is possibly more compliant after fatiguing exercise.

4.1 Force measurements

Main strategy to increase the skiing speed was to increase the cycle rate. Cycle length increased from SLO to MED velocity and mildly decreased to MAX speeds. Changes in cycle are well in line with previous studies (ex. Hoffman, Clifford et al. 1995; Millet, Hoffman et al. 1998). Increased velocity was achieved by change in RFD which roughly doubled between SLO to MED and between MED to MAX conditions while change in MF2 was only 10-20% between different conditions.

Fatigue changed the strategy to achieve the desired speed. In MED condition more force (11.8%) where applied in MF1 following 9% higher RFD in MF2. Change can be a sign of depressed poling action compensated by increased leg action. However, it is impossible to ensure the reason of the shift due the broke of pole force sensor. In MAX situation fatigue velocity was only 0.6% slower than in non-fatigued condition. In contrast to MED situation MF1 (-9.0%) and RFD (-8.8%) were decreased in fatigued condition meaning that poling action was possibly increased from non-fatigued situation. Similar shifts in force production balance changes between upper and lower body have been reported e.g. in Ohtonen, Lindinger et al. (2013) in a study of ski sliding properties effect to technique. Based on shifts in force production it can be proposed that at least some fatigue occurred during the exercise. The reason to the ability to maintain the maximal velocity is most possibly the anti-shock nature of XC-skiing (Millet and Lepers 2004). However the shift in force production to smaller muscles (upper body) most likely causes earlier decrease in performance.

4.2 EMG analysis

Phase pattern is different in all measured muscles. MG (EX2) and VL (EX1) show a clear increase in aEMG during eccentric phase. Respectively RF muscle aEMG increases during concentric phase (CO2). TRI muscle movement requirements are different compared to leg extensor muscles. However, TRI muscle shows clear SSC type of activation pattern were activation in eccentric phase is clearly higher than in concentric phase. Abnormal MG muscle activation level in PRE MAX condition is most probably caused by problem in measurement devices. (figure 2)

Pre-activity increased in all muscles with increasing speed. Leg pre-activation aEMG levels in relation to aEMG levels in first stretch phase were not as high as reported in running (Kyrolainen, Avela et al. 2005). Difference can be result of the lack of the clear braking phase. TRI muscle pre-activation levels are in line with Lindinger, Holmberg et al. (2009). MG, VL and TRI show highest aEMG values in eccentric phase supporting SSC favorable muscle activation behavior during ground contact.

Interestingly MG and VL eccentric and concentric aEMG levels change place between force peaks (MF 1 and MF 2). MG muscle aEMG level was higher in concentric phase near MF1. Order changed near MF2 where higher aEMG is found in eccentric phase. In case of VL behavior changes from more active eccentric phase near MF1 to higher activity in concentric phase near MF2.

Short latency reflex possibly enhanced muscle performance in TRI and VL muscle where aEMG activity after pole/ski plant is high. Timing wise high activity occurs in line with previous studies. VL aEMG is clearly higher in eccentric phase before MF1 compared to MF2. Moreover aEMG level was greatly depleted in fatigued situation what can be the sign of decreased SR activity due the fatigue (Komi 2000).

4.3 Muscle tendon interaction

4.3.1 Vastus lateralis

VL $Length_{MTU}$ behaves with respect to force production. VL prolongs before both MF1 and MF2 and undergoes the change in lengthening direction near both MF1 and MF 2. VL $Length_{MTU}$ is close the same near MF1 and MF2 but minimal length during UPH change respectively to velocity.

VL $Length_{fa}$ starts to shorten clearly before MF1 and MF2 causing that VL $Lenght_{TT}$ shows clear stretch near MF1 and MF2 in MAX condition. $Length_{TT}$ stretch analyze is not so clear in MED and SLO condition due to limitations in analysis. However it can be suggested that MED velocity shows at least some stretch of TT close MF1 and MF2. In SLO condition timing of VL $Lenght_{fa}$ lengthening is close the same than whole $Length_{MTU.}$ That means that even tough analysis shows a great change in VL $Length_{TT}$ it might be more due to analysis limitations. Result is in line with earlier study of Ishikawa, Sano et al. (2010). VL showed similar result than Triceps brachii in earlier study suggesting that role of SSC is more meaningfull in racing and sprinting speeds in VL muscle.

In Fatigued MAX situation $Lenght_{TT}$ undergoes greater stretch close to MF1 than non-fatigued situation. Moreover stretch can be found also near MF2. In fatigued MED condition stretch is possibly also increased near MF2. However, due to problem in measured data angle and muscle information are not perfectly synced.

4.3.2 Medial Gastrocnemius

MG Lenght$_{MTU}$ behavior changes greatly in respect to the velocity. At SLO condition Length$_{MTU}$ stays nearly the same until MF2 where Length$_{MTU}$ does a small lengthening before shortening. In MAX and MED velocities lengthening and shortening are greater also near MF1.

Length$_{fa}$ follows Length$_{MTU}$ during the whole ground contact time. However, MG Length$_{TT}$ undergoes lengthening from the start of the ground contact and changes to the rapid shortening near MF2. MG MG Length$_{TT}$ action is close to a catapult action which had been introduced in human walking (Ishikawa, Komi et al. 2005). MG MG Length$_{TT}$ behavior stays nearly the same in all conditions (intensity and fatigue). Result is possibly in contrast with earlier study where stretch was more rapid in MG. However, difference between demands of the classic and skating technique most probably explains also the difference in results (Ishikawa, Sano et al. 2010).

4.3.3 Rectus Femoris

US depth was not enough deep for RF muscle and inner aponeurosis was only partly visible during ground contact time. Muscle fiber length (RF Length$_{fa}$) was estimated mainly from the distance between inner and superficial aponeurosis. Estimation easily causes over estimation in fascicle length and thus problems to TT length estimation.

However RF Length$_{MTU}$ lengthens before MF1. MTU length is shorter after MF1 but undergoes lengthening and shortening close to MF2. MTU behavior near MF1 stays nearly the same in all conditions. Near MF2 muscle length change in lengthening and shortening greater and faster. In comparison to earlier study, SSC might play less important role in RF during V2 –skate xc-skiing that in diagonal xc-skiing. aEMG analyze also supports the difference because RF is more active during concentric phase.

(Ishikawa, Sano et al. 2010)

RF Length$_{TT}$ possibly stretches near MF1 and after that stretch is lesser. Length$_{fa}$ shows rapid changes during UPH. Taking into account limitations in analysis it is impossible to argue if the changes are possible caused by short latency reflex or e.g. disturbing movement of the US probe.

4.3.4 Triceps Brachii

Model used to calculate TRI MTU limited the estimation on Lenghth$_{MTU}$ to 130 degree flexion. However, elbow angle flexion is much greater near MF (~150 degree). Furthermore pole force sensor broke down during trials and US analysis has been done according to EMG activation. TRI MTU behavior according to raw angle data shows that Lenght$_{MTU}$ must lengthen before shortening phase during ground contact. Furthermore, according to study of Lindinger, Stoggl et al. (2009) MF$_{pole}$ occurs near maximal elbow flexion. On the section were analysis is possible shortening velocity of Length$_{MTU}$ increases according to skiing speed. Lenght$_{fa}$ stays nearly the same during the time where Length$_{MTU}$ analysis limits the calculation of Length$_{TT}$ this indicates that that in all speeds Length$_{TT}$ undergoes stretch near MF$_{pole}$ in all situations. Result is perfectly in line with study of Ishikawa, Sano et al. (2010) where SSC came more meaningful in TRI in competitive speeds.

4.4 Limitations of the study

During the measurements pole force sensor broke down during PRE situation trials causing that accurate analysis for fascicle length was impossible to perform. However, for illustrative purpose analysis was possible when fascicle behavior was estimated straight from the ultrasonogram. Due to the complexity of measurement setup all desired data was not recorded by all measurement systems in all trials. Furthermore in slow velocities US recoding ended before the 3D measurement area and caused that analysis was impossible to do in the same cycle.

Repeatability of US measurement has been confirmed in static situation in different joint angles and in tensed and relaxed muscle. (Fukunaga, Ichinose et al. 1997) However this measurement had challenges caused by demanding dynamic movement and the limited number of samples. Rotations during xc-skiing in muscle can distort the fiber lengths and pennation angels in 2D analyze that can vary with different velocities (Bénard, Becher et al. 2009). Low US sampling rate (72.4Mhz) can limit the measurement of rapid changes in muscle (Ishikawa and Komi 2007). Furthermore even the probe was attached as firmly as possible probe was moving during fast changes of moving direction. Problem was the worst in TRI measurement were ultrasonogram contained blank frames after the pole plant. US probe should be selected more carefully. TRI, RF and VL muscle sonograms contained either lesser part of the muscle fiber or aponeurosis was not visible over the whole cycle. Deficient information of the ultrasonograms made US analysis more difficult or forced the use of inaccurate methods to estimate the fiber length and angle.

Joint angle measurement was calculated straight as angles between markers. When comparing to the data estimated from full body model used in a corresponding measurement. Result showed up to 10% present difference between data estimate by full body model and data estimated straight from the markers. Full body model usage was, however, impossible due the demanding of the US measurement system.

4.5 Suggestions for the further measurements

As a suggestion for further study following changes can be recommended. Use of regular goniometers can be suggested for corresponding studies if full body model is not possible to use. More carefully selected probe size to ensure full visibility of aponeurosis. More carefully attached probe to TRI muscle to avoid plank frames near pole plant phase. TRI MTU length should have more powerful model that allows $\text{Length}_{\text{MTU}}$ estimation in high flexion values. More carefully planned sync and design of the measurement area and devices to ensure that all data is collected from the whole desired cycle.

4.6 Conclusions

Present study suggests that SSC type of behavior is main strategy to muscle increase performance in TRI and VL muscles during V2 xc-skiing. Bi-articular muscles MG and RF showed also stretch during ground contact phase, but behavior of the TT and fascicle did not show clear change with increasing speed. Fatigue possibly depletes the efficiency of SSC, but due the anti-shock nature of xc-skiing SSC type movement can be maintained longer than in ex. running. Furthermore possibly due the lesser muscle damage elastic energy can be used for e.g. sprinting purposes in despite of depleted neural activity.

Comparison of the leg muscle behavior to the existing studies is complicated due the double peaked force production which is unique to the V2 xc-skiing. VL muscle showed clear stretch in TT-fascicle behavior near both force peaks. Stretching of the muscle increased with increasing velocity suggesting that use of elastic energy is used for enhance muscle performance. TRI muscle behavior was similar to VL muscle, but due the limitations in TRI TT-fascicle analyze TT behavior contains more speculation. Bi-articular muscle muscles (MG and RF) do not show clear stretch related change on TT – fascicle behavior. MG MTU showed catapult like action where TT is stretched in the beginning of the ground contact and released in the end of contact phase.

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