NORWEGIAN SCHOOL
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Andreas Skiri Refsdal

Jump performance in Maasai jumpers and Caucasian controls

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Department of Physical Performance
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Summary

Purpose. The purpose of the present thesis was to investigate countermovement jump (CMJ) performance, muscle-tendon morphology and anthropometrics in Tanzanian Maasai individuals and to compare these data to Caucasian controls.

Methods. 28 healthy subjects (Maasai = 20, Caucasian = 8) volunteered for the study. Maximal CMJ performance was evaluated by use of force plate kinetics and kinematics. Timing of muscle activation was examined with electromyography (EMG). Moreover, anthropometric data for the lower leg was acquired, and muscle architecture and tendon dimensions were assessed by use of ultrasound (US). Finally, jump height and joint angles were estimated for the Maasai while performing a traditional ‘jump dance ritual’.

Results. Relative to body height the Maasai had greater foot ($P < 0.001$) and hallux length ($P = 0.019$). The Maasai had shorter lower legs compared to the Caucasians in absolute values ($P = 0.033$) and displayed shorter fascicles and lower muscle thickness for gastrocnemius (GM) and vastus lateralis (VL) both in absolute (GM fascicle length: $P < 0.001$, VL fascicle length: $P < 0.001$, GM thickness: $P < 0.001$, VL thickness: $P < 0.001$) and relative values (GM fascicle length: $P < 0.001$, VL fascicle length: $P = 0.002$, GM thickness: $P < 0.001$, VL thickness: $P = 0.003$). Achilles tendon (AT) aponeurosis length was greater in the Maasai compared to the controls both in absolute ($P = 0.042$) and relative values ($P = 0.005$). Relative to body height AT and AT moment arm length were significantly greater for the Maasai (AT length: $P = 0.014$, AT moment arm: $P = 0.017$). CMJ hip flexion was significantly greater ($P < 0.001$) in the control group. Jump height in CMJ were significantly lower for the Maasai in absolute values (Maasai: 33.3 ± 6.6 cm vs. Caucasian: 40.0 ± 4.9 cm, $P = 0.015$), but relative to body weight (BW) jump height was greater in the Maasai group (Maasai: 0.6 ± 0.1 vs. Caucasian: 0.5 ± 0.1, $P = 0.009$)**.** Duration of the braking and push-off phases were significantly ($P < 0.001$) in the Maasai subjects compared to the Caucasian controls. The EMG-data demonstrated overall ‘wider’ signals for the Maasai group compared to the controls. For 18 Maasai subjects, average jump height during a so-called ‘jump dance ritual’ was 46 cm. Jump height during the ‘jump dance ritual’ correlated positively to BW ($r = 0.68$) and CMJ height ($r = 0.69$).

Conclusion. The Maasai subjects jumped higher in maximal CMJ compared to Caucasian controls when adjusting for BW, and practiced a more upright jumping strategy compared to the controls. In maximal CMJ, the time duration of the braking and push-off phases were shorter for the Maasai subjects. Fascicle length and muscle thickness were less in GM and VL for the Maasai group both in absolute and relative values. The Maasai subjects had a longer AT, AT aponeurosis and AT moment arm relative to body height compared to the controls. Furthermore, jump height during the ‘jump dance ritual’ for the Maasai was remarkable and close to 50 cm. The present study is the first to incorporate precise biomechanical methodology to investigate jumping performance in Maasai individuals, and the results underscore previous notions that the Maasai show good jump performance. The study demonstrates clear differences in anthropometry between groups and combined with the Maasai lifestyle (consisting of traditional jumping rituals and a high volume of daily activity) it sheds light on the factors that underlie the impressive jumping capabilities in Maasai individuals. The Maasai possess significant jumping performance despite no specific strength or plyometric training history as common in western world jumping athletes.

Preface

To be able to conduct this unique investigation along with so many skilled people has been absolutely amazing. It has been a journey through severe planning, preparing of tests, shipping of nearly 200 kg equipment, the trip to Tanzania combined with the actual testing, and moreover writing of the present thesis. Now, it is eventually finished, and in conjunction with this there are some people I would like to gratitude.

To begin with, I would like to thank PhD Jens Bojsen-Møller and PhD Olivier Seynnes. As my main- and co-supervisors, both of you have been a huge support. You have always been available, either at school or via e-mail when it comes to advice and questions, and your ability to critically evaluate everything have been so helpful.

The next person I would like to thank is Associate Professor Dirk Lund Christensen from the University of Copenhagen. You have been an essential mainstay when it comes to actually conducting this project. This man has visited Africa close to twenty times, and has a number of valuable contacts that have been crucial throughout the process. In addition, PhD Per Aagaard and PhD Peter Magnusson have been crucial in the collaboration.

I would also gratitude Senior Engineer Vidar Jakobsen for excellent technical and methodological guidance and support. As my study-partner, I would like to thank Herman Hernæs as well, for both company and assistance. I admire your always positive thinking and wish you all good luck in the future.

Thanks to all Tanzanian helpers, and to all test subjects that voluntarily joined the study, both Maasai and Norwegian. Furthermore, I would like to thank the Norwegian School of Sport Sciences, for economical support and as a matter of fact making this project possible. In the end I would like to say sorry to my fiancée for being a bit busy the last months.. To wrap it up, Tanzania is an amazing and beautiful country full of surprises. I am going to remember this project for the rest of my life.

Andreas Skiri Refsdal, January 2017

Contents

1. Abbreviations

AT	**A**chilles **T**endon
BW	**B**ody **W**eight
CMJ	**C**ounter**m**ovement **J**ump
CSA	**C**ross-**S**ectional **A**rea
EMG	**E**lectro**m**yo**g**raphy
GM	**G**astrocnemius **M**edialis
MTU	**M**uscle-**T**endon **U**nit
MVC	**M**aximal **V**oluntary **C**ontraction
RFD	**R**ate of **F**orce **D**evelopment
SJ	**S**quat **J**ump
SOL	**Sol**eus
SSC	**S**tretch-**S**hortening **C**ycle
TA	**T**ibialis **A**nterior
US	**U**ltra**s**ound
VJ	**V**ertical **J**ump
VL	**V**astus **L**ateralis

2. Introduction

The Maasai people are an ethnic group of semi-nomadic people inhabiting the southern part of Kenya and northern part of Tanzania where they settled a few hundred years ago according to their own history. They essentially came from Nilotic tribes that moved south from Sudan, and then integrated with the Cushitic tribes, which merged the traditions from both groups. The Maasai are well known for their characteristic clothing and customs, in addition to the traditional rituals involving dancing, chanting and repetitive jumping. The jumping tribe rituals are a part of a centuries long tradition that involves a large number of jumps performed over 2-3 days by young male Maasai individuals known as the Morani (15-35 years of age).

Jumping is a natural, but at the same time a relatively advanced type of human movement that requires complex coordination skills between the contractile elements of the upper- and lower-body segments (Markovic, Dizdar, Jukic, & Cardinale, 2004; Sheppard et al., 2008). Preliminary observations by Dirk Lund Christensen (personal communication) suggested jump heights of more than 50 cm during the repetitive Maasai jumping which is similar to maximal countermovement jump (CMJ) performance in elite jumping athletes in the western world (de Ruiter, Vermeulen, Toussaint, & de Haan, 2007). Jump performance in Maasai individuals remain anecdotal as no previous studies have in detail measured jump performance in the Maasai. Furthermore, precise measurement of kinematics and kinetics have not previously been conducted. In addition, existing information about anthropometrical data on the Maasai people is limited, although, one previous study has examined the Maasai foot (Choi, Suh, & Seo, 2014).

The impressive jump performance of the Maasai people could be explained by several factors, but most likely frequent jumping throughout the lifespan and starting from an early age plays a significant role. On our field trip to Tanzania several Maasai individuals reported that they had done regular jumping since approximately five years of age. It is important to state that this remains an approximation, as most Maasai are unaware of their actual biological age. Nonetheless, it seems well established that the Maasai lifestyle, culture and tradition imposes a remarkable specific training load on muscles and tendons, which consequently may influence performance in maximal jumping tasks.

Anthropometric features could also play a role for the superior Maasai jump performance. Kenya is well known for their great athlete runners, especially from the Kalenjin tribe, and both Kenyans and the Maasai people are part of the east African population. Recent studies have reported that Kenyan runners display anthropometrical features of muscle and tendon in the lower leg e.g. longer Achilles tendon (AT) and lower gastrocnemius medialis (GM) pennation angle that enables them to utilize energy efficiently during stretch-shortening cycle (SSC) movements (Sano et al., 2013; Sano et al., 2015). The efficient utilization of elastic energy combined with a greater jump height during repetitive jumps in Kenyan runners have been explained by a high recoil from tendinous tissues (Sano et al., 2013). Hence, it may be assumed that also Maasai subjects obtain and benefit from specific anthropometrical features that contribute to jump performance.

No previous studies have incorporated precise biomechanical methodology to investigate vertical jumps (VJ) in the Maasai. Therefore, one feasible strategy to increase knowledge about aspects of human performance in VJ would be to examine that of Maasai individuals.

2.1 Purpose and hypothesis

The purpose of the present thesis was to investigate CMJ performance, muscle-tendon morphology and anthropometrics in Tanzanian Maasai individuals and to compare these to Caucasian controls.

It was hypothesized that the Maasai individuals displayed distinctive anthropometrical features (e.g. a longer AT moment arm and shorter fascicles) and a significant jump performance.

The present thesis is a part of a more extensive biomechanical study where the overall purpose was to compare jump-performance during maximal and repetitive jumping, muscle-tendon-function during jumping, and mechanical properties of the force bearing tissues of the triceps surae in Tanzanian Maasai jumpers and Caucasian controls.

The current thesis consists of a manuscript written as a scientific article (introduction, methods, results and discussion), in addition to a more comprehensive theory and methods chapter.

3. Theory

The theory part of this thesis will focus on determinants of performance for human VJ, such as muscle, tendon, power, force, moment arms and SSC. Eventually, a review of VJ and the cultural setting of the Maasai people will be presented.

3.1 Muscle

The human body has more than 660 skeletal muscles that function in careful concert to enable precise control of human movement. The main function of skeletal muscle is to exert force and produce mechanical work (Zatsiorsky & Prilutsky, 2012). Muscles are able to exert force while shortening (concentric action), lengthening (eccentric/plyometric action) or while maintaining a constant length (static/isometric action) (Levangie & Norkin, 2011).

Muscles adapt quickly to changes in training, loading and immobilization (exposure to bed rest) (Dawson et al., 1998). Muscle strength, speed and power (force x velocity) are three essential physiological factors when it comes to performance in a number of sports, especially in typical force related activities like jumping, sprinting and weight lifting. In general, athletes with a high relative (strength/body weight (BW)) lower-body strength are fast, strong and powerful.

3.1.1 Muscle structure

Skeletal muscles are highly organized, both at micro- and macro-level (Lieber & Friden, 2000). Muscles consist of muscle cells, also known as fibers, running longitudinally in parallel (either parallel to muscle direction of force or somewhat oblique). Each individual fiber is enclosed in a tubular membrane called sarcolemma and surrounded by collagenous tissue named endomysium. The endomysium and sarcolemma are connected by the basal lamina, which plays a special role in the force transmission from the fiber. Several fibers form fascicles, which is bundles of fibers (Lieber, 2002) enclosed within sheaths of connective tissue known as perimysium. Muscle fibers may span the full length of the fascicle, or end somewhere intermediate (Hijikata & Ishikawa, 1997). The whole muscle is surrounded by connective tissue called epimysium, which is continuous with the fascia, a fibrous envelopment that binds nearby muscles together (Figure 1) (Zatsiorsky & Prilutsky, 2012).

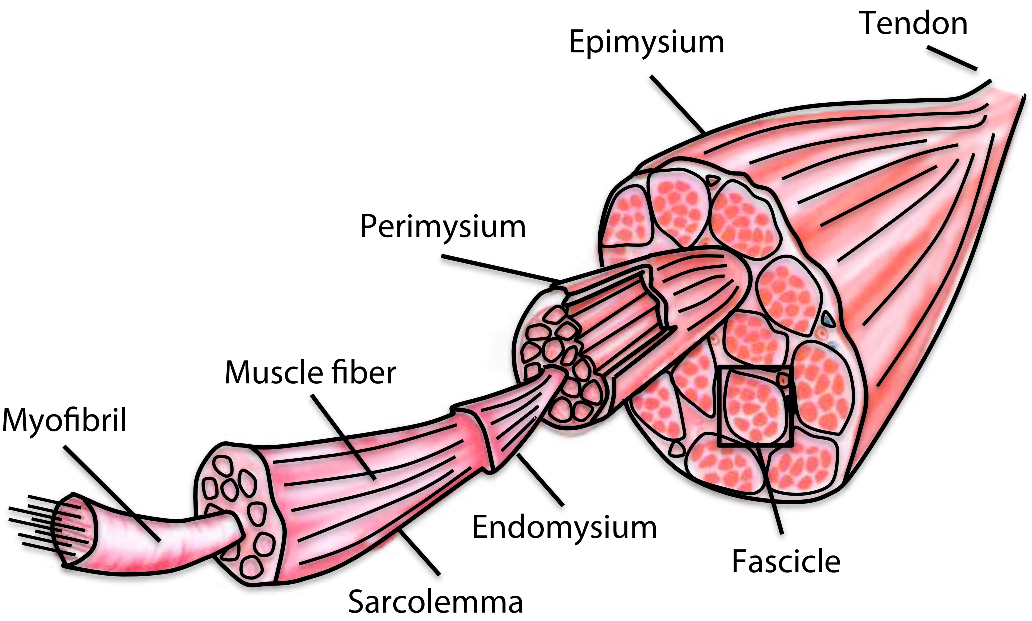


Figure 1: *Structural elements of skeletal muscle.*

Muscle fibers consist of myofibrils that in turn are made of sarcomeres, being the contractile unit of the fiber. Sarcomeres are individually separated by Z-lines, and contains two major protein filaments, actin and myosin, which makes up the basis for muscle contraction. During muscle contraction specific myosin heads attach to the actin filament and by use of adenosine triphosphate (ATP) a force is exerted between the structures which induces relative sliding between the filaments. Myosin and actin are therefore called contractile proteins. When a muscle is contracted or elongated, overlapping of the cross-bridges increase or decrease. If a muscle is lengthened beyond its ideal range of force production, the force output will be lower (Figure 2) (Gordon, Huxley, & Julian, 1966; Podolsky & Shoenberg, 1983).

Muscle tissue demonstrate elastic properties (known as passive properties of muscle) and are affected by several structures and mechanisms. Although tendons are the main contributor to elasticity, some series elastic components are found within the cross-bridges, in the crosslinks between actin and myosin, and in the non-contractile proteins of the cytoskeletons (Gajdosik, 2001; Roberts, 2002). The parallel elastic components include deformation of connective tissues both within and about the muscle (Gajdosik, 2001; Horowits, Kempner, Bisher, & Podolsky, 1986). When a muscle is stretched from its resting length, the passive properties of the muscle contributes to the force output. The relation between force and length of a muscle is known as the force-length relationship (Figure 2).

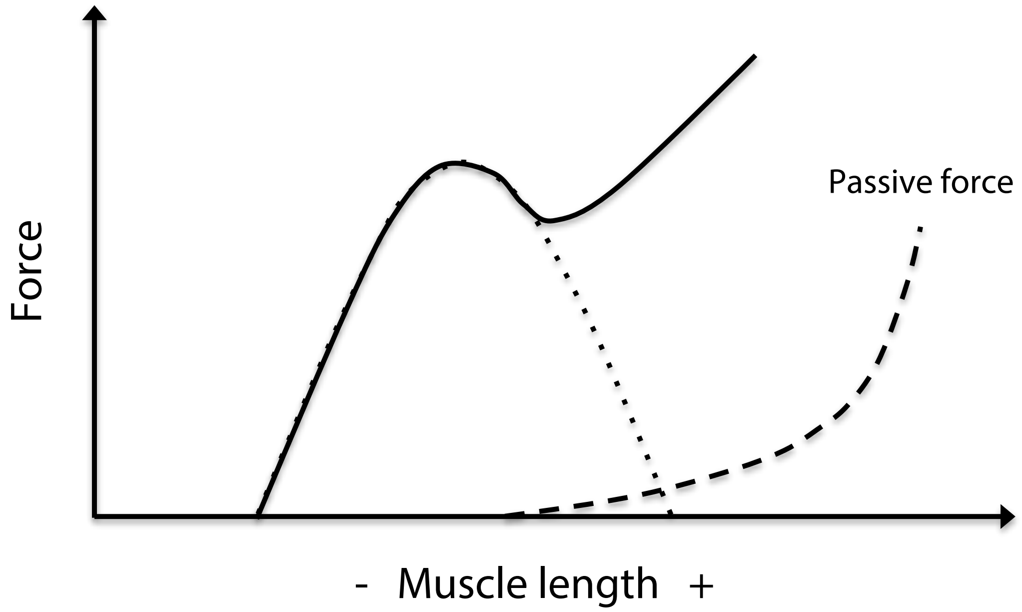


Figure 2: *The force-length relationship of muscle. The dotted line represents the force-length relationship of a single muscle fiber and the dashed line shows the elastic properties as a result of passive force. The solid line represents the force-length relationship of muscle combining both factors.*

3.1.2 Muscle fiber types

Muscle fiber types vary between muscle groups and among individuals, and can be divided into two main types; slow twitch (Type I) and fast twitch (Type II) fibers (Lieber, 2002; MacIntosh, Gardiner, & McComas, 2006). Fast twitch fibers are further categorized into Type IIA and Type IIX fibers. This classification is related to the time duration of the single twitch contractions. Slow twitch fibers have a relatively long contraction-time and low force production, but are highly oxidative and very endurable. Type IIA fibers have a faster contraction-time and higher force production than Type I fibers, but are less endurable. Type IIX fibers have the fastest contraction-time and highest force output of the three types, but are glycolytic and gets rapidly fatigued (Dahl & Rinvik, 2010). Type IIA fibers are considered twice as fast as Type I, while Type IIX is 3-4 times as fast as Type I fibers (Levangie & Norkin, 2011; Raastad, Paulsen, Refsnes, Rønnestad, & Wisnes, 2010). Since power output is related to force and velocity, muscles or individuals with a large amount of fast twitch fibers are likely to be able to generate more power compared to muscles mainly consisting of slow twitch fibers (Wilson et al., 2012).

3.1.3 Morphological properties

Muscle-tendon morphology is the description of muscle or tendon dimensions and architecture, such as volume, length or physiological cross-sectional area (CSA). This includes the term muscle architecture (arrangement of muscle fibers relative to the force axis), which in addition refer to fascicle length and pennation angle (Lieber & Friden, 2000). CSA has a direct relationship to how much force a muscle is able to produce, and together with fiber length and maximum force these factors affect the shortening-velocity and thus the power output (Lieber & Friden, 2001). The pennation angle, i.e. angle muscle fiber insertion into the tendon, may influence contractile force and velocity (Cormie, McGuigan, & Newton, 2011). Muscle architecture might affect functional characteristics, and can be modified with repeated mechanical stimuli through training (Aagaard et al., 2001). Modern ultrasound (US) technology makes it possible to investigate muscle architecture *in vivo* both during rest, passive motions and active tasks (Kubo, Kawakami, & Fukunaga, 1999).

Fibers inside a single fascicle are parallel, but fascicle-arrangement in the whole muscle may vary. Several muscle-forms exist, but the two main types are the parallel and pennate muscles (Levangie & Norkin, 2011). In parallel muscles, fascicles are distributed along the line of muscle force action, and shortening of individual muscle fibers can be translated to shortening of the entire muscle (MacIntosh et al., 2006). Pennate muscles have their name from the Latin word *penna*, which means, 'feather'. Here, the fibers lie angled to the line of muscle-action, and the direction of fiber shortening and tendon movement are different. Hence, more fibers can be arranged into a given volume of a muscle, and the potential force output is greater than in parallel muscles of the same volume (Zatsiorsky & Prilutsky, 2012). Muscle force usually increases with larger pennation angles up to approximately 45 degrees (Alexander & Vernon, 1975). Moreover, this results in fewer sarcomeres in series, which moderates the velocity of the muscle contraction. Every muscle shape thus has some advantages and some disadvantages that affect the functional performance (Wickiewicz, Roy, Powell, & Edgerton, 1983). High-intensity strength training has shown increased pennation angles in human vastus lateralis (VL) after 35 days (Seynnes, de Boer, & Narici, 2007).

Both dimensions and architecture of muscle changes with body size (Kubo, Kanehisa, Kawakami, & Fukanaga, 2001). According to cross-sectional studies, muscle fascicles are longer in subjects that have been practicing strength training for several years (Abe, Kumagai, & Brechue, 2000; Kumagai et al., 2000). Several studies have reported longer muscle fascicles in sprinters compared to anthropometrically matched controls (Abe et al., 2000; Raastad et al., 2010). In addition, studies have demonstrated a statistically significant negative relationship between fascicle length and personal 100-meter record i.e. longer fascicles corresponds to a faster 100-meter record (Abe, Fukashiro, Harada, & Kawamoto, 2001; Kumagai et al., 2000).

Muscle fascicles seem to optimize their length based on the muscle properties and the conditions the muscle is mostly exposed to. In general, long muscle fascicles contribute to greater mechanical power output and faster shortening velocities in comparison with short fascicles due to several sarcomeres in series. The individual sarcomere shortening velocity is slower in longer fascicles than in shorter fascicles given the same shortening velocity, as the sarcomeres in long fascicles operate closer to isometric muscle work and thus are able to generate more force (due to the force-velocity effect) (Kumagai et al., 2000; Stafilidis & Arampatzis, 2007).

3.2 Power and force

Power is a physical variable based on the rate of work per time unit or with other words, the relationship between force and velocity *(force x velocity = power).* The unit of power is watt (W). High power can be achieved with either high force or great velocity, or a combination of both. For human muscle, power is normally highest when contractile force and contraction velocity are at roughly one third of maximal (Cormie et al., 2011). Muscle morphology is consequently an important factor when it comes to maximal muscle power (Kraemer & Newton, 2000).

Early findings claims that it is a special relation between these variables, which means that an optimal distribution of force and speed should be obtained to optimize power production (Hill, 1938). Distribution varies between individuals according to characteristics and training background, but in general, stronger and/or slower subjects reach maximal power at lower speeds than faster subjects (Hill, 1938).

In addition to maximal strength, neural activation properties may play an important role in explosive activites (Cormie, McGuigan, & Newton, 2010; Kraemer & Ratamess, 2004). The nervous system controls the activation of muscles through motor unit recruitment, in addition to frequency and synchronization of action potentials (Cormie et al., 2010). In sports, great forces at high velocities are required to generate maximal power in a shortest amount of time possible. Studies have reported a strong relationship between maximal strength and power in athletes, which assume that a high level of strength is desirable for high power output (Cormie et al., 2011; Manson, Brughelli, & Harris, 2014).

The relationship between force and velocity is known as the muscle force-velocity curve and is illustrated in Figure 3. At the highest velocity of shortening, no force is produced, which means that maximum velocity only can be attained with no load on the muscle. When shortening velocity decreases, the force that the muscle can develop increases. At zero velocity, the muscle works isometrically. The amount of force a muscle can develop increases dramatically and finally forms a plateau when the muscle is lengthened actively (eccentric contraction) (Hill, 1970).

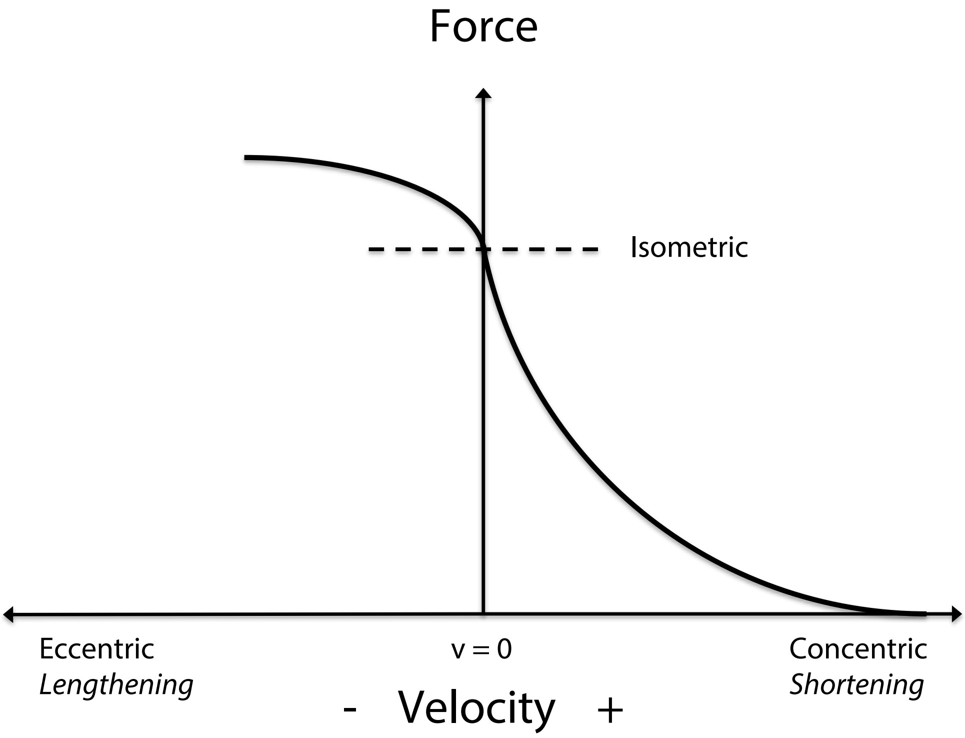


Figure 3: *Force-velocity relationship of muscle. In concentric contractions force declines as velocity increase. In eccentric contractions force increase as velocity increases.*

3.3 Tendons

Muscles are attached to bones via tendons. Knowledge about tendons, both when it comes to structure and mechanical properties is therefore crucial when it comes to understanding VJ. Tendons are viscoelastic structures that allow transfer of occasionally substantial mechanical force (contractile muscle force) into movements about joints (Fung, 1967). An example is the AT which while performing activities like jumping and running can be loaded up to 12 times BW (Komi, 1990; Kongsgaard, Nielsen, Hegnsvad, Aagaard, & Magnusson, 2011).

Tendon tissue is organized in a hierarchical manner almost similar to muscle tissue, from small collagen fibrils to an entire tendon. There are several types of fiber-forming collagen. The most common type is type I, which makes up 95% of the collagen in the body (Myllyharju & Kivirikko, 2001). The non-fiber-forming collagen on the other hand, plays an essential role in healing tendons, lubricating the fibers and regulating fiber diameter (Wang, Guo, & Li, 2012). Tendon fibrils are orientated in all three dimensions inside the fibers and have a diameter of 30-130 nm (Bertolotto et al., 1995). The collagen fibrils form a collagen fiber, which is the smallest collagenous structure that can be tested mechanically (Józsa & Kannus, 1997; Kannus, 2000). Several collagen fibers are bound together by the endotenon, which forms a subfascicle, which again forms fascicles (Butler, Grood, Noyes, & Zernicke, 1978; Józsa & Kannus, 1997; Kannus, 2000). These fascicles form tertiary bundles, which in turn make up the tendon (Butler et al., 1978; Józsa & Kannus, 1997). Tendons are enclosed by white fibrous sheath called epitenon (Kannus, 2000; Levangie & Norkin, 2011).

Most of the dry mass of a tendon consists of collagen and elastin, 65-80% and 1-2% respectively (Kannus, 2000; Kirkendall & Garrett, 1997). Between collagen fibers and fibrils there are proteoglycans. These essential proteins are able to hold water up to 50 times their own weight, and enable the collagen fibrils to withstand remarkable compressive and tensile forces (Józsa & Kannus, 1997). Proteoglycans also contribute to tendon healing and enhance the mechanical stability (Józsa & Kannus, 1997; Wang et al., 2012). Elastin allows a tendon to retain its pre-stretched length after loading (Wang et al., 2012).

Tendon cells mainly consist of tenocytes and tenoblasts, which basically are elongated fibrocytes and fibroblasts between the collagen fibers (Kannus, 2000). The tenocytes main purpose is to repair and maintain structure composition of the tendon by producing collagen, elastin, proteoglycans and matrix precursors (Józsa & Kannus, 1997; Kirkendall & Garrett, 1997; Wang et al., 2012).

As mentioned earlier, tendons are viscoelastic, which means that they combine the properties of elasticity and viscosity (Nordin & Frankel, 2001). Hence, the mechanical behavior depends on the mechanical rate of force the tendon is exposed to (Fung, 1967). Important functions are the ability to store and release elastic energy by loading/unloading (stretching and shortening) the tissue (Kuitunen, Ogiso, & Komi, 2011; Maganaris, 2002; Roberts, 2002) and the property of energy loss known as hysteresis (later explained) (Zatsiorsky & Prilutsky, 2012). Moreover, the muscle-tendon unit (MTU) as a whole is able to dissipate (take out energy) when required e.g. during high force collisions or landings (Alexander, 1991). In contrast to fluid-like substances, elastic substances do return to the original form after being exposed to stress (Józsa & Kannus, 1997).

When a force acts on an object, it produces deformation (Hooke, 1678). In tendons, tensile force leads to elongation. The load-deformation curve illustrates load (force) plotted against deformation, providing essential information about the properties of the particular material (e.g. a tendon) (Figure 4) (Butler et al., 1978). The plot shows the elasticity, plasticity, strength, stiffness and failure point of the material, as well as the amount of energy that the material can absorb before it fails.

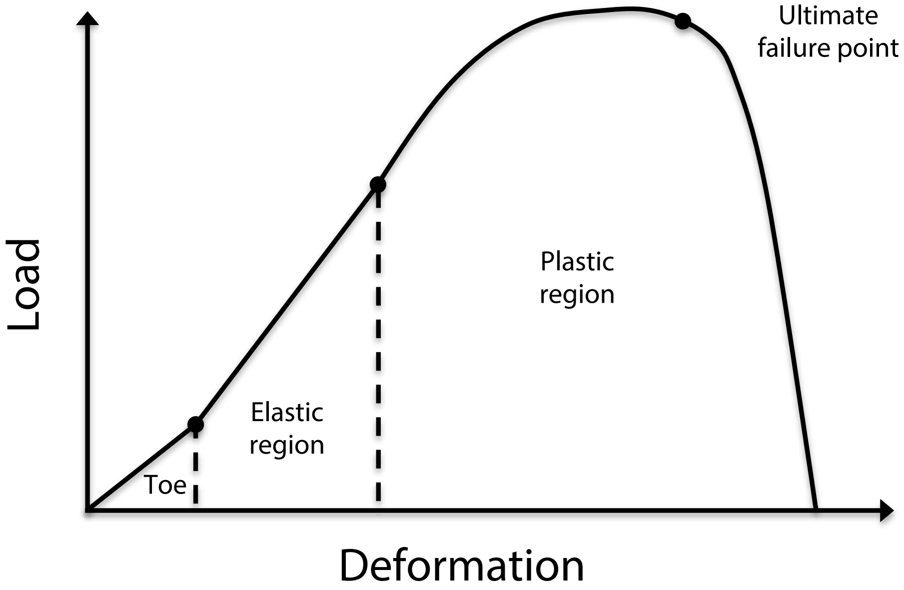


Figure 4: *Basic load-deformation curve for a connective tissue, including the toe, elastic and plastic region.*

Tendon stiffness can be defined as the relationship between tendon force and tendon length (slope of the load-deformation curve), usually expressed in Nmm^{-1}. Tendon compliance, on the other hand, is reciprocal (mmN^{-1}). These variables are calculated from the relationship between load and deformation.

To further understand and describe human tendon function the terms stress and strain are frequently used. Stress is the load force a material is subject to divided by the CSA, usually expressed as psi or MPa. Stress causes a material to change shape or deform, which is known as strain. Hence, strain is the lengthening of the material divided by the original length expressed in % (Butler et al., 1978). At low strain rates, tendons are more deformable than at high strain rates, which affect the energy effectivity and absorption (Butler et al., 1978; Wang et al., 2012). The relationship between stress and strain in a material is often illustrated in a stress-strain curve. A typical stress-strain curve for tendons is presented in Figure 5, including the toe, linear and plastic region (Butler et al., 1978).

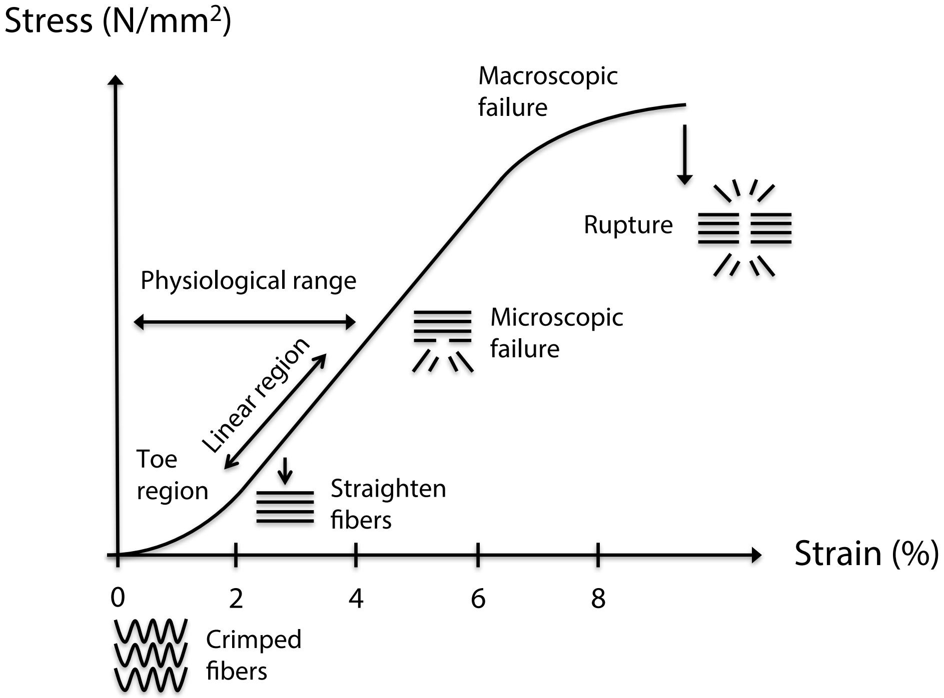


Figure 5: *Relationship between stress and strain in a tendon, including toe, linear and plastic region of the tendon.*

In the toe region, fibers are being stretched from wave-forming to running in parallel. In this region, the strain increases at a higher rate than the stress. Studies have shown that the strain varies between 1.5-4% in the end of the toe region (Butler et al., 1978; Viidik, 1973). Consecutive to the toe region a linear region is found, which means that a further elongation gives a stiffer tissue. The linear region has a strain limit of 2-5% (Butler et al., 1978; Maganaris, 2002; Rosager et al., 2002), and here the force needed to extend the material by some distance is proportional to the distance (Hooke´s law) (Viidik, 1973). In the stress-strain curve this principle is known as Young´s modulus (slope of the stress-strain plot), which makes it possible to compare properties between tendons with different dimensions (in relation to the material) (Viidik, 1973).

In the end of the linear region, a yield point is found, where macroscopic fiber failure occurs unpredictable ultimately leading to complete failure (strain > 10%) (Maganaris & Paul, 1999). When complete rupture of the tendon occurs, the load-bearing abilities are lost. The strain values previously mentioned corresponds to collagen fibers tested alone. If we include whole tendons, *in vitro* studies have shown values much higher, actually as much as 20-50% (Butler et al., 1978).

The amount of stress and strain depends on tendon size and composition. Tendons with greater CSA can withstand more force with less deformation than a structure of the same original length with less CSA (Figure 6-a). If two tendons are composed of the exact same material, the tendon with greater CSA will have greater stiffness (in relation to the structure), and the longer tendon will be less stiff (Figure 6-b) (Butler et al., 1978).

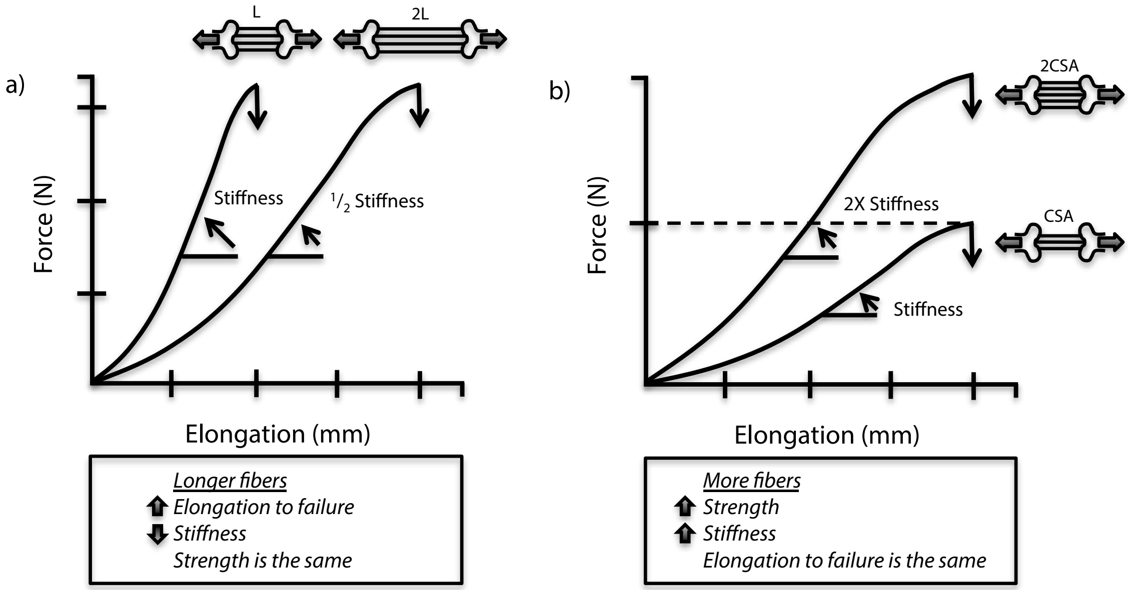


Figure 6: *Tendon CSA and length affects the overall response to load. a) Increasing tendon length means it can elongate further given the same loading conditions. b) Increasing CSA means the tendon can withstand more force at any given length.*

When force and length of a tendon are measured during both loading and unloading, the resulting curves do not follow the same path. This concept is known as hysteresis, which is defined as the difference between the loading and unloading curves in the stress-strain cycle (hysteresis-loop) (Figure 7). The hysteresis-loop illustrates energy loss during a deformation cycle, mainly caused by conversion of mechanical work into heat. The hysteresis is a result of inability of a tendon to follow identical paths upon application and withdrawal of force. When a tendon is stretched, the area beneath the force-deformation curve represents the mechanical work done to lengthen the tendon. The force during loading is larger than the force during unloading, given the same amount of tendon extension (Zatsiorsky & Prilutsky, 2012).

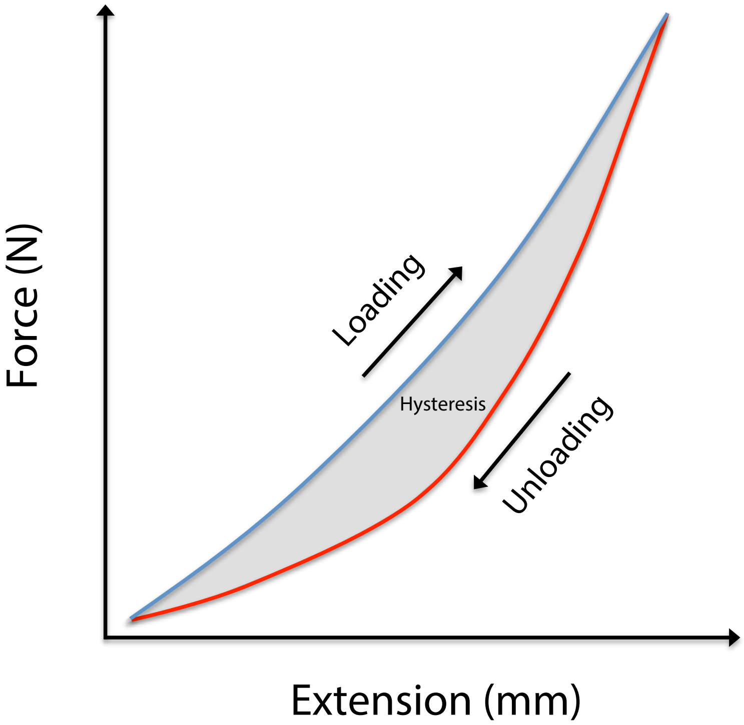


Figure 7: *Hysteresis-loop: The force-deformation curves are different for the loading and unloading periods. The area of the hysteresis loop is representativse of the energy loss.*

Tendons exact role during human movements has not been known until quite recent years. This is greatly related to the recent technology-improvement in US, which has made it possible to study tendons *in vivo* (Kubo et al., 1999). From present knowledge, there is no doubt that the MTU system has to undergo several demands in different sports and activities. Tendon stiffness seems to influence the function of the tendon, and the CSA plays an important factor. It is crucial to point out that it is not just the muscle or the tendon alone that decides how the system works, but a complex interaction between groups of muscle, tendons, ligaments, bones and cartilage (Biewener & Roberts, 2000).

3.4 Moment arms

To initiate movement, skeletal muscles develop forces that produce motions in the skeletal system (Yamaguchi, 2001). The muscles attach to bones at a given distance from the center of rotation of the joint. Therefore, linear tension developed by a muscle is transformed into rotational joint moment. The joint moment produced by a muscle is thereby the product of the force carried by the muscles, tendons and the moment arm of the MTU about the center of rotation (Baxter & Piazza, 2014). Moment arm length is defined as the perpendicular distance from the MTU line of action to the center of rotation of the specific joint, and is responsible for converting muscle force and linear displacement to joint moment and rotation (Baxter & Piazza, 2014).

The muscle moment arm variation affects the actual change in fiber length when it comes to a given joint rotation and has consequently potential to modulate the useful force production when performing a jump. In long muscle fibers with a proportionally bigger moment arm, the shortening velocity of the sarcomeres will be unaffected by the difference in fiber length. Additionally, short moment arms emphasize the benefits of long muscle fibers during a concentric contraction by a lower shortening velocity in the sarcomeres (Lee & Piazza, 2009). The moment arm can not be changed voluntarily (e.g. by training), but may change throughout the range of motion of a joint (Zatsiorsky & Prilutsky, 2012).

Recent papers have showed a range in plantarflexor moment arms between 3.7 and 6.1 cm (Maganaris, Baltzopoulos, & Tsaopoulos, 2006; Sano et al., 2015). Longer moment arms results in greater plantar flexor moment for a given muscle force, but it also determines the speed at which the plantar flexors shorten during plantar flexion. This is why muscles with long moment arms will shorten faster during the same joint rotation and therefore generate less force as a result of the force-velocity relation (Lee & Piazza, 2009). Although short moment arms reduce the mechanical advantage, it enhances muscle force generation during contractions performed at high shortening velocities in combination with long fibre lengths (Lee & Piazza, 2009).

In the horizontal plane, the center of rotation runs close to the center of both malleoli (Lundberg, Svensson, Nemeth, & Selvik, 1989). In addition, the center of rotation changes with the amount of plantar flexion (Maganaris, Baltzopoulos, & Sargeant, 1998). Both US (Fath, Blazevich, Waugh, Miller, & Korff, 2010), magnetic resonance imaging (MRI) (Baxter, Novack, Van Werkhoven, Pennell, & Piazza, 2012; Maganaris et al., 1998), x-ray (Lundberg et al., 1989) and perpendicular images using a measure board (Scholz, Bobbert, van Soest, Clark, & van Heerden, 2008) can be used to determine AT moment arm length. When using a measuring board, the AT moment arm can be determined as the mean average distance from the two malleoli to the posterior part of the AT (Scholz et al., 2008).

Moment arm length has an essential impact on jumping height, especially in movements involving SSC (Scholz et al., 2008). Moment arm length cannot change as such, but changing the position of a joint or adjusting the movement to a different technique (e.g. jumping with less knee flexion), may modulate the moment arm (Maganaris, Baltzopoulos, & Sargeant, 2000). At the same time it is complicated since also muscle contractile properties change. It might be that training optimizes this interplay to enhance power output.

3.5 Stretch-shortening cycle

The understanding of the muscle mechanics during human locomotion is an ongoing challenge (Ishikawa & Komi, 2008). Muscles and tendons play different roles, but functionally these tissues are closely integrated (Roberts, 2002).

SSC, or reversible muscle action, refers to a movement where a muscle which is pre-activated, goes through stretching or elongation in the braking phase prior to active shortening during a push-off phase (Ishikawa & Komi, 2008). The stretching in the braking-phase enables storage of elastic energy in the tendons that subsequently is used as mechanical energy during push-off (Kuitunen et al., 2011; Roberts, 2002). SSC may contribute to a reduction in muscular mechanical work by enhanced economy and makes the muscle fibers work closer to isometric which potentially can produce greater force (Roberts, 2002; Stafilidis & Arampatzis, 2007).

The typical Hill curve changes when accounting for the MTU as a whole. During the braking phase, the MTU system experiences negative work followed by a quick release of elastic energy during the push-off phase, which again lead to a higher force compared to muscle action alone (Figure 8) (Finni, Ikegawa, Lepola, & Komi, 2003; Ishikawa, Finni, & Komi, 2003; Komi, 2000).

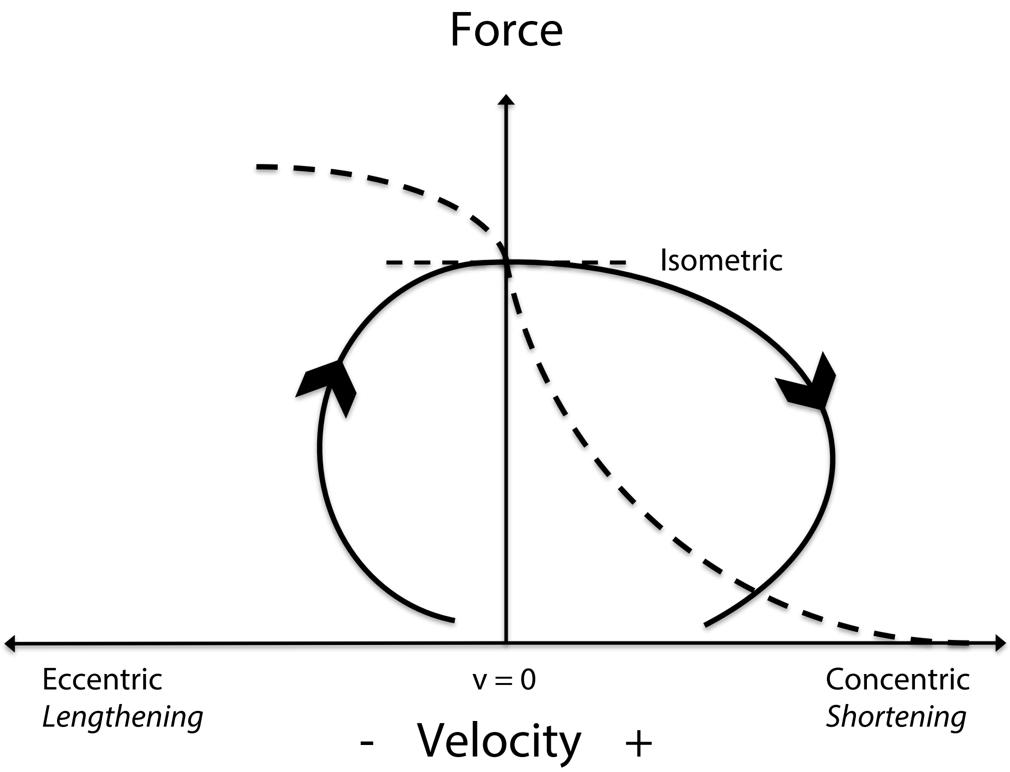


Figure 8: *Relationship between force and velocity during a SSC movement. Upward deflection signifies stretching, and downward deflection signifies shortening of the MTU.*

When pre-activated muscles are being stretched prior to shortening, the performance will be enhanced during the concentric phase of the movement. This has been established in both *in vivo* and *in vitro* muscle experiments and is claimed to be a result of stored strain energy in the elastic tissues of the muscles (Asmussen & Bonde-Petersen, 1974; Cavagna, Dusman, & Margaria, 1968; Komi & Bosco, 1978). Moreover, VJ is a central human movement where elastic energy storage and utilization is thought to be important (Bobbert, Huijing, & van Ingen Schenau, 1986).

3.6 Vertical jumping

The VJ is a movement where an individual jumps vertically to achieve the highest point above the ground. It is an advanced human movement that requires complex coordination between upper- and lower-body segments. To achieve a high VJ, the aim is to create a great vertical acceleration before leaving the ground. A massive acceleration contributes to a high initial vertical velocity, which makes the center of mass reach higher. To achieve this acceleration, the subject has to produce a significant amount of force in the shortest time possible (Ziv & Lidor, 2010).

A number of biomechanical and physiological factors influence jump performance, like force, power, rate of force development (RFD) and coordination of the upper- and lower-body segments, but ultimately, jump height (vertical displacement of the center of mass from take-off to the apex of the flight) is determined by the vertical velocity of the center of mass at take-off (Dowling & Vamos, 1993; Hopkins, 2000). Investigations have demonstrated that the amount of fast-twitch muscle fibers relate statistically significant to VJ performance (Bosco & Komi, 1979). In addition, positive correlations have been reported between VJ height and lower extremity musculature strength (Jaric, Ristanovic, & Corcos, 1989). Furthermore, studies have also found that a lower body fat percentage corresponds to a better VJ performance (Caia et al., 2016; Davis, Briscoe, Markowski, Saville, & Taylor, 2003). Despite this, peak power might be one of the best predictors of jump performance, even when compared to force output (Dowling & Vamos, 1993). Typically, good jumpers achieve higher joint moments, power and work done at the ankle, knee and hip than less talented jumpers (Vanezis & Lees, 2005).

Several different jump techniques exist, although the most used in testing are the CMJ, the squat jump (SJ) and the drop jump. Peak force may reach 2-3 times BW during CMJ and SJ (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005; Kirby, McBride, Haines, & Dayne, 2011) and close to 5 times BW for the drop jump due to the elevated starting position (Dobbs, Gill, Smart, & McGuigan, 2015). Higher force leads to a greater stretch and load on the tendons (e.g. the AT) (Bobbert, Mackay, Schinkelshoek, Huijing, & van Ingen Schenau, 1986), which subsequently may contribute to an increased amount of elastic energy (Fukashiro, Komi, Jarvinen, & Miyashita, 1995). Thus, a drop jump test may involve other physiological and musculoskeletal qualities than during the CMJ and SJ (Arampatzis, Schade, Walsh, & Bruggemann, 2001). Variables like jump depth, duration of jump phases and jump strategy may vary between individuals (Anderson & Pandy, 1993; Bobbert, Casius, Sijpkens, & Jaspers, 2008).

It is generally accepted that maximal VJ provides a reliable and sensitive assessment of different kinematic and kinetic variables (Markovic et al., 2004; Sheppard et al., 2008). Because of this, the VJ is one of the most popular methods for indirect assessment of lower-limb maximal power in populations of different age, gender and training status (Asmussen & Bonde-Petersen, 1974; Bobbert, Gerritsen, Litjens, & Van Soest, 1996).

Both VJ performance and power of the leg muscles are considered important elements for athletic performance and for carrying out daily tasks and activities (Bobbert, 1990; Hruda, Hicks, & McCartney, 2003). Due to this, a number of studies have been conducted using VJ ability as a screening method in different sports like volleyball, basketball and athletics (Ziv & Lidor, 2010). In addition to being a predictor of sports performance, tests like this can identify strengths and weaknesses in athletes, and contribute to optimize training programs (Hara, Shibayama, Takeshita, & Fukashiro, 2006).

VJ is not only used for sports and training purposes, but also for testing the force, velocity and power production capacity of leg muscles (Sheppard et al., 2008). In laboratory conditions, VJ height is normally determined using a force platform. This is considered the gold standard and is usually consisting of a metal plate with piezoelectric or strain gauge transducers attached at each corner, which gives an electrical output proportional to the forces exerted against the plate. The most used technique to determine jump height is the impulse-method. This method is agreed to be both valid and reliable and is based on the relationship between impulse and momentum by integrating the net vertical force acting on the jumper prior to takeoff to estimate the takeoff velocity. The velocity is then used in a projectile motion equation to determine the actual jump height (Anderson & Pandy, 1993; Hatze, 1998; Kibele, 1998).

A number of parameters can be derived from maximal jumping on a force plate, like jump height, power, acceleration, maximum force, RFD and peak velocity. These values can be reported in absolute terms or relative to BW, and described separately for different phases of the jump. Several investigators have examined the relationships between these parameters (Cormie, McBride, & McCaulley, 2009; Dowling & Vamos, 1993).

3.6.1 Countermovement jump

Human motor tasks like jumping and throwing are typically started with a so-called countermovement, e.g. a movement in the opposite direction to the goal direction. Improved task performance has been established by such a countermovement (Bojsen-Moller et al., 2005).

A CMJ is a VJ involving significant downward motion of the center of mass of the body prior to upward propulsion. More specifically it is a movement where the subject starts at an upright standing position with arms akimbo, then followed by a countermovement of acceleration below the center of gravity achieved by a rapid downward movement flexing the knees to about 90 degrees (Figure 9) (Cavagna et al., 1968; Thorlund, Michalsik, Madsen, & Aagaard, 2008). Subjects are normally instructed to jump maximally. Agonist muscles and tendons are being stretched during descent (eccentric phase), which is beneficial because of an accumulation of elastic energy that can be used when going upwards in the concentric phase. The actual SSC in this movement is relatively long (> 0.25 seconds) (Bobbert et al., 1996; Bosco & Komi, 1979). CMJ performance and the effects of this type of jump have been investigated for several years (Bobbert & Casius, 2005; Bosco & Komi, 1979; Fukashiro & Komi, 1987).

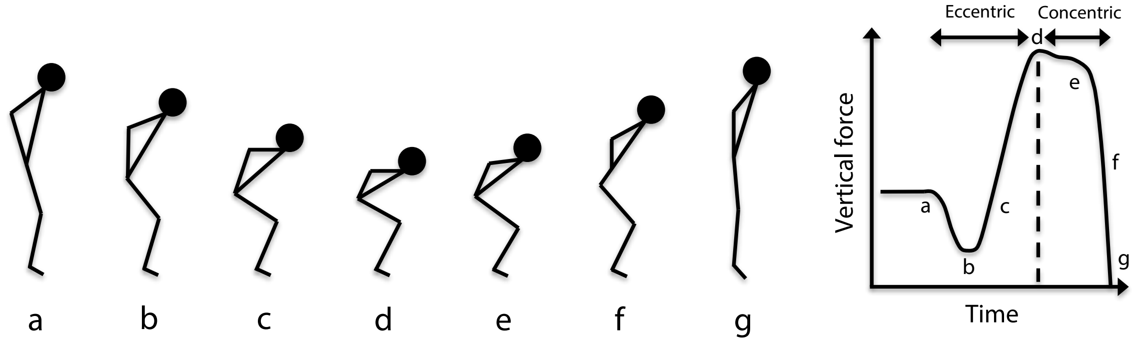


Figure 9: *Body position and basic force curve during ground contact phase in a CMJ.*

Recent findings demonstrate that male volleyball players can achieve CMJ heights (with arms akimbo) close to 50 cm and CMJ with arm swing exceeding 60 cm (de Ruiter et al., 2007; Gheller et al., 2015).

3.6.2 Squat jump

The SJ is a movement where the subject is jumping from a static position, usually with the knees at an angle of approximately 90 degrees, the trunk relatively vertical and arms akimbo throughout the jump to minimize any influence from the arms (Figure 10). It is crucial that the jump is performed without any countermovement, which means that only the concentric action of the agonist muscles is involved in the movement. Most individuals need a considerable amount of learning before the SJ movement can be performed correctly. Even well trained individuals with extensive practice and encouragement may experience minor amount of countermovement during the SJ

(Bobbert & van Zandwijk, 1999). Despite this jump movement is slightly artificial and rarely used in pratice, it is widely used as a training exercise for explosive development of the leg muscles, as well as a test of leg power (Sheppard et al., 2008). Findings have demonstrated SJ heights near 45 cm in male college level volleyball players (Gheller et al., 2015).

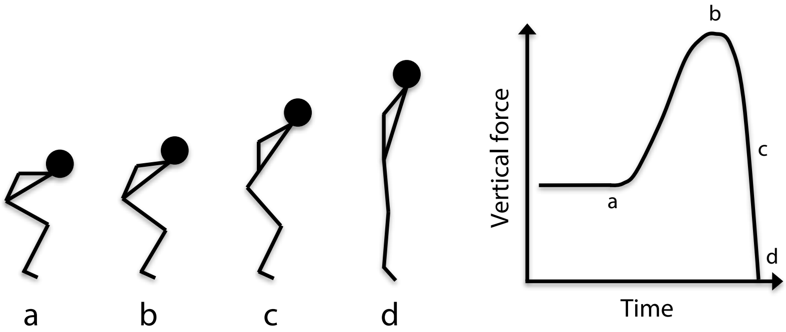


Figure 10: *Body position and basic force curve during ground contact phase in a SJ.*

3.6.3 Countermovement jump vs squat jump

A key difference between the CMJ and SJ is the use of SSC and subjects are thus able to jump higher in a CMJ than in a SJ (Bobbert et al., 1996). Furthermore, jump height is heavily influenced by the amount of squat depth prior to push-off in both CMJ and SJ i.e. that a deeper squat depth (up to 0,75 m) corresponds to improved jumping performance (Kirby et al., 2011).

When it comes to work output, it has been reported that the greater jump height in CMJ compared to SJ is due to a higher work output of the hip extensor muscles. This is explained by that the extensor muscles have a higher active state in a CMJ than in a SJ in the first 30% of the shortening phase (Bobbert & Casius, 2005; Fukashiro & Komi, 1987).

There are several different possible explanations of this. The first is basically related to that the subjects are not used to the jump technique, and therefore unable to coordinate the jump. A non-optimally controlled jump could reduce the effective energy contributing to the jump height. Intersegment coordination could also influence the jump performance (Vanezis & Lees, 2005).

Another explanation could be that during a SJ, the muscles are not able to initiate a high level of force prior to the concentric contraction. It takes some time before a muscle reaches its maximum value in a maximal voluntary contraction (MVC). This is related to muscle activation by the nervous system (stimulation dynamics), time constants of the stimulation-active state coupling (excitation dynamics) and interaction between contractile elements and series elastic elements (contraction dynamics). If active state begins simultaneous as the force rises, some of the shortening distance of the MTU is traveled at a submaximal force, and means that the work produced is submaximal (van Ingen Schenau, 1984). This could be avoided by allowing muscles to build up maximum active state before the concentric contraction starts. This is exactly what happens in a CMJ (Bobbert et al., 1996).

A third potential explanation is related to the storage and reutilization of elastic energy (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978). During a CMJ the active muscles gets pre-stretched in the eccentric phase and therefore absorb energy which is partly temporarily stored in the series elastic elements and later reutilized in the concentric phase. Research has argued that this contributes to increase the work produced in a CMJ compared to a SJ (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978).

Another cause could be that the stretching of the mucles that take place in a CMJ triggers spinal reflexes and long-latency responses that increase the muscle stimulation in the concentric phase (Dietz, Schmidtbleicher, & Noth, 1979; Jones & Watt, 1971). Because of this increased stimulation, muscles might produce more force, and therefore more work.

A final probable reason is that the muscle pre-stretch that accours in a CMJ modifies the contractile properties, due to potentiation. Potentiation is an enhancement that increases with the velocity of pre-stretch and decreases with the time-duration after the pre-stretch (Edman, Elzinga, & Noble, 1978). Studies have shown higher force produced by artificially stimulated isolated muscles when pre-stretched (Cavagna, Citterio, & Jacini, 1975). This force enhancement in CMJ could help to increase the work produced in CMJ compared to the SJ (Bobbert et al., 1996).

3.7 Rate of force development

An essential role in the maximal muscle power development is played by the contractile RFD. RFD is defined as the rate of force increase in a given time interval (relative or absolute), and is a relevant parameter to measure neuromuscular performance of athletes in sports that involve explosive muscle contractions (Stone et al., 2003). RFD can also be defined as the ability to produce muscle force rapidly (Kraemer & Newton, 2000; Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002).

Some studies have shown that RFD is an important performance variable in VJ (Bojsen-Moller et al., 2005; McLellan, Lovell, & Gass, 2011b; Vanezis & Lees, 2005), while others have reported a poor relationship between RFD and VJ (Lees, Vanrenterghem, & De Clercq, 2004; Stone et al., 2003). This lack of significant relationship between RFD and VJ may be a result of methodologic problems related to the measurement (McLellan, Lovell, & Gass, 2011a).

Acceleration in the initial phase of a movement is determined by the RFD, and this variable ultimately alter the velocity (Kraemer & Newton, 2000; Aagaard et al., 2002). This underlines the fact that a high RFD is beneficial in short and fast movement, especially in movements where the range of joint motion is limited. RFD is just like muscle power and strength dependent on muscle morphology and neuromuscular function like motor unit firing frequency and agonist-antagonist muscle co-activation (Kraemer & Newton, 2000; Aagaard et al., 2002). Training of strength and power may lead to increased RFD during jumping and isometric tests (Cormie et al., 2009; Aagaard et al., 2002).

3.8 Summary - Jump performance parameters

In conclusion, to achieve a high VJ, the ultimate aim is to create a great vertical acceleration before leaving the ground (Dowling & Vamos, 1993; Hopkins, 2000). There are several parameters that may contribute to this. Muscle force, power and RFD are key elements that may affect jump performance (Kraemer & Newton, 2000). These factors can be modified by e.g. CSA, fascicle length, pennation angle and/or muscle fiber type. Tendon morphology and an optimized strategy of series elastic elements loading are likewise important as it may alter the ability to store and release elastic energy (e.g. hysteresis and stiffness) (Maganaris, 2002; Roberts, 2002). Furthermore, moment arm length can enhance the muscle mechanical advantage. Moreover, neural activation properties and movement strategy (coordination of the upper- and lower-body segments) is crucial (Cormie et al., 2010). Additionally, low body fat and and a good BW to power ratio is approved to be beneficial (Vanezis & Lees, 2005).

3.9 Electromyography

Surface electromyography (EMG) is an accepted and highly used method to record neural activation of skeletal muscle (Clarys & Cabri, 1993). With neural activation, the change in electrical potential may be recorded across the skin. The EMG-signal contains detailed information about the synaptic inputs received by the motor neurons and the electrical properties of the muscle fibers (Farina, Merletti, & Enoka, 2014). EMG-amplitude is only relevant to a reference EMG from maximal contraction of the same muscle (Burden, 2010). The amplitude is further expressed as a proportion of this reference, usually in percentage (Clarys & Cabri, 1993). EMG-activity comparison between a given contraction and an isometric MVC is a highly used method to normalize EMG (Burden, 2010). This is also the method recommended by the SENIAM *(Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles)* project (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000).

Crosstalk from nearby muscles may impair surface EMG-signals. It has been shown that approximately 17% of electrical activity from adjacent muscles may be detected on the surface of the muscle of interest (De Luca & Merletti, 1988). To substantially reduce the likelihood of detecting crosstalk signals, electrodes should be placed at the largest part (intermediate) of the muscle belly (De Luca, 1997).

In biomechanics, surface EMG is commonly used as an indicator of muscle activation initiation, to determine force production of a muscle or to identify muscle fatigue. If no reliable maximal EMG-data can be recorded through MVC, the most applicable factor to investigate is muscle activation timing e.g. during gait or in movements like jumping or running (De Luca, 1997). This is considered as the simplest application of surface EMG as it reduces the information content of the EMG to a binary signal indicating the on-off status of a muscle (Farina, 2006).

3.10 Maasai

The Maasai people are an ethnic group of semi-nomadic people inhabiting the southern part of Kenya and northern part of Tanzania, but settled in this area just a few hundred years ago according to their own history. They essentially come from Nilotic tribes that moved south from Sudan, and then integrated with the Cushitic tribes, which merged the traditions from both groups. The Maasai are well known for their characteristic clothing and customs. Some tribes invite tourists from all over the world to come visit their village for an in-depth experience of the Maasai traditions, culture and lifestyle (Akama, 1999).

Maasai lifestyle is based on cattle, which also is their main foodsource. Meat, milk and occasionally blood from the animals basically make up the traditional diet (Orr & Gilks, 1931). Due to a general decrease in cattle more recently, several tribes have started to grow food like rice, potatoes, sorghum and cabbage. A Maasai´s wealth is basically measured in terms of the amount of cows and children. A respectable number of cows are about 50, and the more children the better. Despite relatively large herds of cows, the per capita income of the Maasai is very low (Briggs, 2006).

The Maasai people are also known for their traditional rituals involving dancing, chanting and repetitive jumps (Figure 11). Young men, approximately between 15-35 years are the tribe-warriors (jumpers), also known as the Morani, are the performers of the repetitive jumps during the rituals. During the ‘jump dance rituals’, the Morani stand in a circle or line while performing the *adumu* or *aigis*, which basically means, 'to jump'. One at a time the warriors jump as high as possible in front of the rest of the tribe. After a couple of jumps, the next warrior takes over. While jumping, the jumpers sway their body slightly back and forth and move the neck systematically while breathing in and out. Throughout the ceremony the tribe incorporate music consisting of a deep rhythm created by chanting and grunting. Based on the height of the jumps, the tribe sometimes raises the pitch of their voices (Jordania, 2011).

Figure 11: *Maasai jumpers during the traditional 'jump dance ritual'. (Photo: Andreas Skiri Refsdal)*

Preliminary observations by Dirk Lund Christensen (personal communication) suggested jump heights of more than 50 cm during the repetitive Maasai jumping which is similar to maximal CMJ performance in elite jumping athletes in the western world (de Ruiter et al., 2007). Jump performance in Maasai individuals remain anecdotal as no previous studies have in detail measured jump performance in the Maasai. Furthermore, precise measurement of kinematics and kinetics have not previously been conducted. In addition, existing information about anthropometrical data on the Maasai people is limited, although, one previous study has examined the Maasai foot (Choi et al., 2014).

4. Methods

This study is part of a larger investigation on the Maasai people administered and funded by the Norwegian School of Sport Sciences, the University of Southern Denmark, Institute of Sports Medicine Copenhagen at Bispebjerg Hospital and the University of Copenhagen. Principal investigator of the overall study is Associate Professor Dirk Lund Christensen (Section of Global Health, University of Copenhagen). The study was in part funded by the Danish Ministry of Culture.

4.1 Study design

The present study was an experimental non-invasive study exclusively investigating anthropometrics, maximal jumping and the traditional Maasai 'jump dance ritual' comparing Maasai jumpers and Caucasian controls. A brief overview of the overall test procedures is displayed in Figure 12. For the full experimental protocol see Appendix 2.

***Figure 12:** Brief overview of the test procedures in the Maasai investigation.*

As mentioned, the present thesis is a part of a larger investigation. The description of methods below focuses thus on procedures relevant for the purpose of the present thesis.

4.2 Recruitment

The Maasai subjects were recruited through local project collaborators in the Monduli region of Tanzania. Norwegian subjects were recruited through oral and written communications at the Norwegian School of Sport Sciences.

A total of 28 subjects volunteered for the study. Subjects were initially divided into three groups: 1) Maasai (n=20), 2) Norwegian jumping athletes (n=4) and 3) Norwegian control group (n=4). Inclusion criteria were male subjects between 18-40 years of age without any injuries and with the ability to perform the relevant protocol. Due to a relatively small number of subjects in the two Norwegian groups (jumping athletes and controls), these groups were for the present thesis pooled into a single group hereafter referred to as the Caucasian group (n=8).

Maasai subjects (age: 26.5 ± 6.0 yr, height: 170.1 ± 7.0 cm, weight: 55.8 ± 6.7 kg) were young athletic males (Maasai jumpers) from traditional Maasai communities in the outskirts of Monduli in the Arusha Region of Tanzania. Monduli is situated in the northern part of Tanzania, west of mt. Kilimanjaro. All Norwegian subjects (age: 23.4 ± 2.4 yr, height: 183.5 ± 5.9 cm, weight: 85.0 ± 10.3 kg) were students from the Norwegian School of Sport Sciences. The experienced jumpers were active elite athletes on national level in sports like volleyball, basketball, sprinting and long jump and had been active in different jumping activities, depending on their sport. The subjects in the control group were recreationally active in mainly strength training, but not specifically in jumping movements. Norwegian subjects were told to restrain from heavy strength training 24 hours prior to testing.

All subjects signed a written informed consent form (Appendix 3). One form was made in Norwegian for the Norwegian participants, and another one in Swahili for the Tanzanian participants. The forms contained information about the purpose of the study, risks associated with participating and information about anonymization of collected data. The study included only previously used and safe non-invasive methods, and the risk of injury related to testing was therefore considered minimal.

The study was conducted in accordance with the guidelines of the Declaration of Helsinki and was examined by relevant ethics committees in Tanzania (Appendix 4). In addition, all subjects were informed that they were allowed to withdraw from the study at any time and without any special reason.

4.3 Measurements

4.3.1 Anthropometric measures

Body height was measured in an upright standing position to the nearest 0.1 cm with a portable stadiometer (Meterex II, D97, UNICEF, Copenhagen, Denmark). BW was measured to the nearest 0.1 kg with a portable high precision scale (BWB-800 SMA, Tanita, Tokyo, Japan).

AT length was measured with the subjects lying prone on a bench with the feet over the edge (mid shank) to ensure a neutral ankle joint position. A LogicScan 128 US-system (EXT-1Z, Telemed, Lithuania), including a linear 60 mm transducer (HL9.0/60/128Z-2, Telemed, Lithuania) with a scanning frequency of 12 MHz was used to locate the insertion of the AT on the calcaneus. The probe was moved proximally to the most distal insertion of soleus (SOL) on the AT. Both points were marked with a pen, and the distance was measured externally and taken to represent the free AT length. The AT aponeurosis length was determined by moving the US-probe proximally to identify the most distal insertion of the GM on the AT, which was marked with a pen and subsequently the distance from the SOL insertion to the GM insertion was measured thus identifying the aponeurosis length (Stafilidis & Arampatzis, 2007). US-images of the resting muscle architecture (muscle thickness, fascicle length and fascicle pennation angle) were acquired at the largest part of the muscle bellies (approximately at the lower 30% of muscle length in GM and 40% for the VL) (Abe et al., 2000; De Luca, 1997).

To measure foot length, hallux length and AT moment arm, a custom-built measurement board was used (Scholz et al., 2008) (Figure 13). The subjects were instructed to stand upright on the board aligning the lateral and subsequently the medial part of the right foot with the edge of the plate. The tip of both the lateral and medial malleoli and the tip of the first metatarsal were marked with a pen. Digital images were taken of the foot medially and laterally with different centers of the photo to minimize image distortion. Lower leg circumference was measured at 10% increments of the lower leg using a measuring tape. Lower leg length was defined as the distance from the tip of the lateral malleolus to the lateral epicondyle of femur, while upper leg length was defined as the distance from the lateral epicondyle of femur to the trochanter major. Anatomical landmarks were identified by palpation, and length was measured using a measuring tape.

Figure 13: *Lateral and medial view of the right foot of a Maasai subject standing upright on the custom-built measurement board. The AT moment arm was determined from medial and lateral images by measuring the horizontal distance from the malleoli to the posterior aspect of the AT. Foot length was calculated from the medial view images. Hallux length was calculated from medial view images with the hallux in center of the image.*

4.3.2 Kinematic measures

Kinematic data were obtained two-dimensionally from reflective markers placed on six different anatomical landmarks (acromion, trochanter major, lateral epicondyle of femur, lateral malleolus, calcaneus and fifth metatarsal) using three Oqus 400 cameras (Qualisys, AB, Gothenburg, Sweden) (Figure 14 and 15). Markers had a diameter of 12 mm, and identification of the anatomical landmarks was made by palpation. Sampling frequency was set to 300 Hz. Calibration of the recorded area was done using a reference frame on the force plate, and a calibration-wand. Motion data was exported directly to the motion analysis software Qualisys Track Manager (Qualisys, AB, Gothenburg, Sweden).

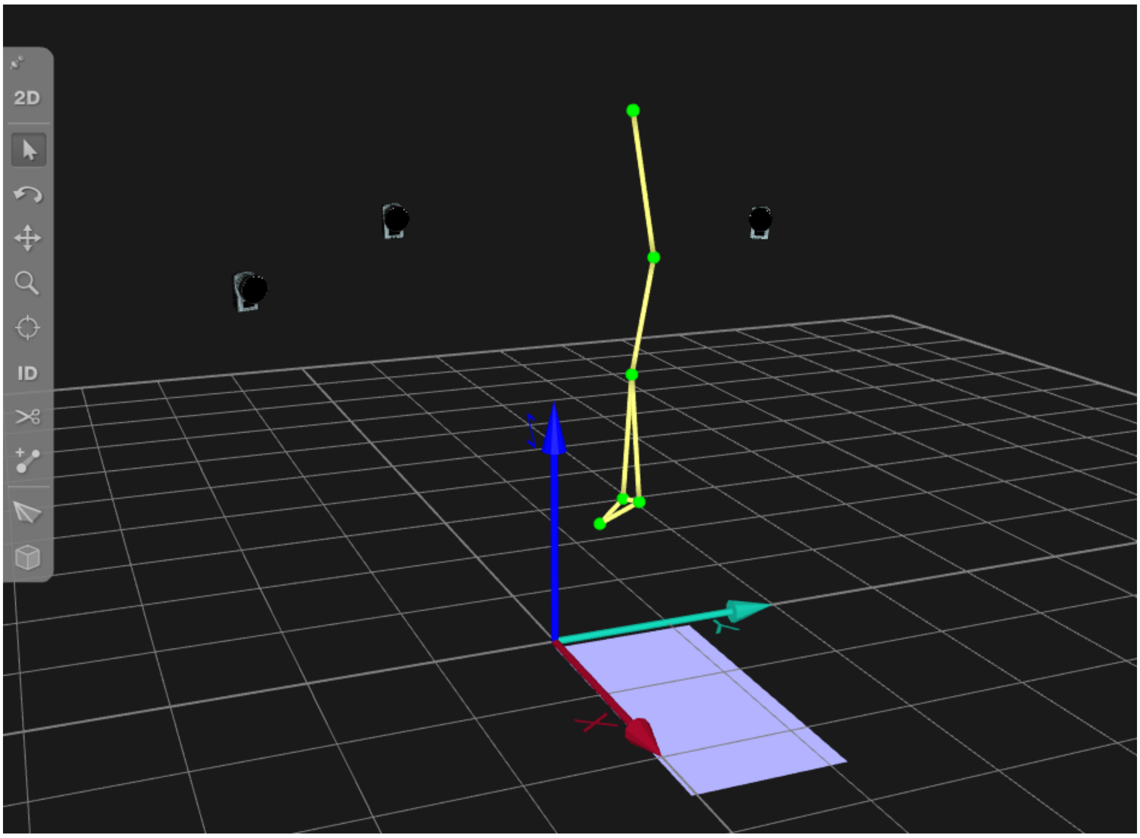


Figure 14: *Screen-shot of the position data of a subject during flight time in Qualisys Track Manager. The setup of the three cameras used for kinematic recordings can be seen in the background. The light blue area in the bottom of the picture represents the force plate.*

During Maasai ‘jump dance ritual’ testing, only one reflective marker at the acromion were attached to each subject. A smartphone (Apple iPhone 6, Apple, Cupertino, USA) recorded video in the sagittal plane at 240 fps for post-hoc manual analysis of jump height and joint-angles of the ankle, knee and hip. A video tracking software was used for the analysis (Tracker, Video Analysis and Modeling Tool, Open Source Physics).

4.3.3 Kinetic measures

Subjects tested in Norway at the Norwegian School of Sport Sciences completed the jump tests on an AMTI BP6001200 force plate (AMTI, Watertown, MA, USA) leveled to the ground. Data sampled in Tanzania was captured on a custom-built force plate fabricated in a lightweight design (Biomekanikk AS, Oslo, Norway). As the force plate could not be lowered into the ground in Tanzania, a lightweight frame of plywood and Styrofoam surrounded the plate to minimize the risk of injury (Figure 15). Sampling frequency was set to 300 Hz for both force plates. All recorded analog kinetic data were sent to an USB analog board (S/N 8161, Qualisys, AB, Gothenburg, Sweden), converted to digital signals and finally exported to the motion analysis software Qualisys Track Manager. Timeframes of the Oqus 400 cameras were matched to the USB analog board using a sync cable.

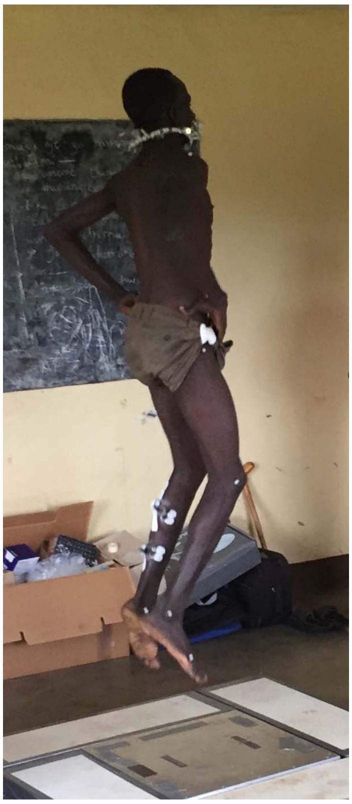


Figure 15: *Maasai during the CMJ flight phase. The light-weight force plate including the plywood and Styrofoam frame can be seen in the lower portion of the image. Placement of the reflective markers is visible on the right side of the subject.*

4.3.4 Electromyography

Surface EMG was sampled from the left leg VL, GM, SOL and tibialis anterior (TA) using bipolar surface electrodes (Neuroline 720 72000-S, Ambu, Ballerup, Denmark) (electrode material: Ag/AgCl, size: 45 x 22 mm) with an inter-electrode distance of 20 mm. Signals were sent from a wireless transmitter (Noraxon DTS EMG, Noraxon Inc., Scottsdale, AZ, USA) to a receiver (Noraxon TeleMyo DTS Desk Receiver, Noraxon Inc., Scottsdale, AZ, USA) connected to a computer. Electrodes were placed according to SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) project (Hermens et al., 2000). Prior to electrode placement the skin was shaved and cleaned with ispropanol to reduce skin impedance. Sampling frequency was set to 1500 Hz, and EMG-data were exported directly to the Qualisys Track Manager.

4.4 Protocol overview

The Norwegian subjects met once in the biomechanic lab at the Norwegian School of Sport Sciences and the Maasai subjects met once in the field lab in Monduli Juu. The complete test duration was approximately two hours. A brief overview of the test procedures in the present study is displayed in Figure 16.

***Figure 16:** Brief overview of the test procedures in the present study.*

CMJ were performed on a force plate from an upright standing position with arms akimbo to minimize any influence from the arms. The subjects kept their feet parallel at a distance equal to the width of their shoulders. Following a signal from the test-leader, the subjects made a rapid downward movement by flexing their hip, knees and ankles and then immediately jumped as high as possible. The subjects were generally instructed to jump as high and as fast as possible and otherwise use their preferred jumping technique.

During the subsequent Maasai 'jump dance ritual' testing, the subjects (only Maasai) were instructed to jump as close to their normal ritual despite the somewhat awkward situation of being in the lab (Figure 17). Subjects were allowed to carry both their stick, knife and full clothing while jumping, and a group of Maasai were chanting and dancing close by to resemble the jumping ceremony. It was thus not possible to attach reflective markers to their lower extremities however, one marker was attached to the acromion. The force plate was positioned in the middle of the test area, and all subjects were lined up in order to jump. Each subject completed a few repetitive maximal jumps on the force plate, one at a time.

Figure 17: *Maasai jumper during 'jump dance ritual' testing. (Photo: Andreas Skiri Refsdal)*

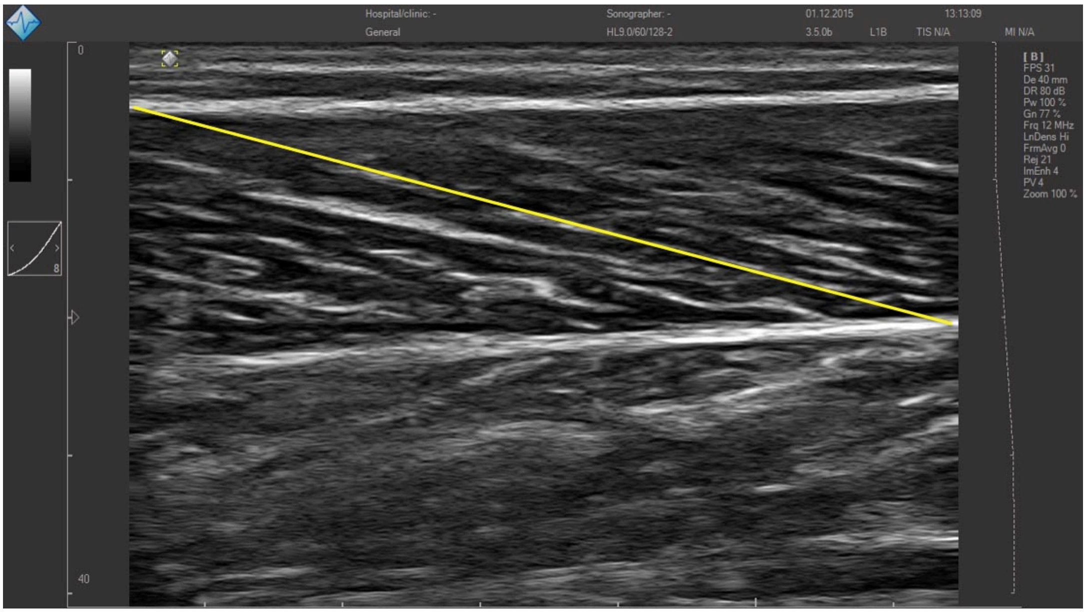
Both groups completed a maximal SJ test. Subjects were asked to keep their hands on the hip and look straight ahead. After a clear signal from the test-leader, subjects were instructed to slowly flex their knees, stop for a few seconds and then jump as high as possible while trying to avoid any countermovement. To ensure a somewhat similar starting position, all subjects were instructed to start the jump with a knee angle of approximately 90 degrees. Hip angle was self-determined. The outcome from this test was not successful or valid, as the Maasai were unable to execute the SJ movement without a countermovement in the beginning of the jump, despite having up to five attempts. In consequence, no SJ data were included in the present results.

4.5 Analysis and statistics

4.5.1 Anthropometric data

AT moment arm, foot length and hallux length was calculated from images using ImageJ (National Institutes of Health, Maryland, USA). AT moment arm was considered as the average value of the distance between the tip of the medial and lateral malleolus to the most posterior aspect of the AT (Sano et al., 2015; Scholz et al., 2008).

Foot length was determined as the distance between the most posterior point of the heel and the most anterior point of the hallux. Furthermore, hallux length was defined as the distance between the most prominent aspect of the first metatarsal and the most anterior point of the hallux. Resting muscle architecture was calculated from US-images using ImageJ (Figure 18). To ensure an accurate measurement fascicle length (minimal out-of-plane error), the US-probe was aligned with the muscle fascicles (Benard, Becher, Harlaar, Huijing, & Jaspers, 2009). Both resting fascicle length and resting pennation angle was calculated three times from the same image for each subject and then averaged. Muscle thickness measurements were based on perpendicular images of the muscle belly and calculated identically as the resting fascicle length and resting pennation angle. Relative lower leg circumference was calculated as the percentage of the greatest individual circumference for each measurement site, before averaging data for each group.


Hospital/clinic: -
General
Sonographer: -
HL9.0/60/128-2
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13:13:09
3.5.0b
L1B
TIS N/A
MI N/A
[B]
FPS 31
De 40 mm
DR 80 dB
Pw 100 %
Gn 77 %
Frq 12 MHz
LnDens Hi
FrmAvg 0
Rej 21
ImEnh 4
PV 4
Zoom 100 %

Figure 18: *US-image of GM resting muscle architecture. Includes a line along the path of a muscle fascicle in order to calculate muscle fascicle length.*

4.5.2 Kinematic data

Position data were low-pass filtered (Butterworth second-order with a cut-off frequency of 5 Hz). Joint angles were calculated from the position of three markers for each joint: Ankle joint angle; lateral epicondyle, lateral malleolus and fifth metatarsal. Knee joint angle; trochanter major, lateral epicondyle and lateral malleolus. Hip joint angle; acromion, trochanter major and lateral epicondyle. Length of GM MTU was calculated using the following formula (Hawkins & Hull, 1990):

$$L = C0 + C1\alpha + C2\beta + C3\beta^2 + C4\phi$$

$$GM\ MTU\ length = 0.900 + 0\alpha - 6.20E\text{-}4\beta + 0\beta^2 + 2.14E\text{-}3\phi$$

(α, β, φ represents hip, knee, and ankle joint angles at any given time)

As only one reflective marker was used while performing the traditional jump dance ritual, the analysis was done manually: Videos were examined frame by frame, extracting still images from the bottom position of each jump. A total of 337 jumps were analyzed. Only full cycle jumps were used in the results, eliminating the first takeoff and last landing of each jump cycle. Ankle, knee and hip angles were determined manually by use of digital imaging software (ImageJ). Approximately the same anatomical landmarks as described in the previous paragraph were used (Figure 19).

Figure 19: *Estimation of joint angles (ankle, knee and hip) in the bottom position of a jump during the traditional Maasai 'jump dance ritual'.*

4.5.3 Kinetic data

All subjects performed 3-5 CMJ, were the highest jump was selected for statistical analysis (Thorlund et al., 2008). Force data were filtered with a Butterworth second-order low-pass filter (cut-off frequency 100 Hz). The impulse-method was used to estimate jump height, where net vertical force acting on the jumper prior to takeoff was integrated in order to estimate takeoff velocity. Takeoff velocity was later used in a projectile motion equation to determine jump height (Anderson & Pandy, 1993). Maximal force was determined from the force signal and maximal power was calculated as the product of force and velocity. RFD was calculated as the average tangential slope at 0-100 ms relative to the start of the eccentric deceleration phase (return of body mass) (Thorlund et al., 2008). The onset of jump was determined as the time point where the mass of the subject was 5 N below body mass and take off was identified as the time point where the ground reaction force reached below 40 N (Street, McMillan, Board, Rasmussen, & Heneghan, 2001).

'Jump dance ritual' jump height was calculated as the difference between the vertical position of the reflective acromion marker in the upright standing position and the highest point of the jump. A 701.6 mm wand-stick was used as a reference length within the obtained video.

4.5.4 Electromyography

EMG-data were band-pass filtered (10-500 Hz) and subsequently a Butterworth second-order low-pass filter was applied. As the Maasai were unfamiliar with MVC, unfortunately no maximal EMG-data could be reliably obtained. Therefore the analysis of EMG-data was limited to timing patterns of muscle activation during CMJ. Relative EMG was thus based on peak values obtained during maximal jumps for each subject (ranging from 0-100%).

4.5.5 Corrections to body size

Based on dimensional theory (Jaric, 2003; Markovic & Jaric, 2004), data were expressed both in absolute and relative values using allometric parameters. The equation P/BW^{ap} (P = respective parameter, BW = body weight and ap = allometric parameter) was used to obtain the normalized value.

4.5.6 Statistics

Differences between groups were analyzed using an independent samples t-test. The overall alpha level was set to $P \leq 0.05$ for determination of statistical differences. To determine the relation between relevant parameters, linear regression analyses were performed using the Pearson product moment correlation coefficient (r) (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analyses were performed in IBM SPSS Statistics 24 (International Business Machines, Armonk, New York, USA). Results are reported as means ± standard deviation (SD) unless otherwise stated.

4.5.7 Validity and reliability

Validity is related to whether a test actually measures the trait it is supposed to measure, and reliability concerns the accuracy and dependability of the results of a test (Thomas, Nelson, & Silverman, 2011). When applying the impulse-method with a force plate sampling frequency of 300 Hz, the combined maximal potential error is approximately 2% (Street et al., 2001). Furthermore, previous investigations have observed a coefficient of determination of $r^2 = 0.81\text{-}0.98$ and a coefficient of variation of 12.6% (Bojsen-Moller et al., 2005). Both validity and reliability are reported to be good for US measurements of muscle thickness, fascicle length and fascicle pennation angle (Ishikawa & Komi, 2007; Kwah, Pinto, Diong, & Herbert, 2013; Seynnes, Maganaris, de Boer, di Prampero, & Narici, 2008). Moreover, surface EMG is considered a valid and reliable method for measuring muscle activation in leg muscles during motion (Fauth et al., 2010).

References

Abe, T., Fukashiro, S., Harada, Y., & Kawamoto, K. (2001). Relationship between sprint performance and muscle fascicle length in female sprinters. *J Physiol Anthropol Appl Human Sci, 20*(2), 141-147.

Abe, T., Kumagai, K., & Brechue, W. F. (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Med Sci Sports Exerc, 32*(6), 1125-1129.

Akama, J. S. (1999). Marginalization of the Maasai in Kenya. *Annals of Tourism Research, 26*(3), 716-718.

Alexander, R. M. (1991). Energy-saving mechanisms in walking and running. *J Exp Biol, 160*, 55-69.

Alexander, R. M., & Vernon, A. (1975). The dimensions of knee and ankle muscles and the forces they exert. *Journal of Human Movement Studies, 1*, 115-123.

Anderson, F. C., & Pandy, M. G. (1993). Storage and utilization of elastic strain energy during jumping. *J Biomech*.

Arampatzis, A., Schade, F., Walsh, M., & Bruggemann, G. P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr Kinesiol, 11*(5), 355-364.

Asmussen, E., & Bonde-Petersen, F. (1974). Storage of elastic energy in skeletal muscles in man. *Acta Physiol Scand, 91*(3), 385-392. doi:10.1111/j.1748-1716.1974.tb05693.x

Baxter, J. R., Novack, T. A., Van Werkhoven, H., Pennell, D. R., & Piazza, S. J. (2012). Ankle joint mechanics and foot proportions differ between human sprinters and non-sprinters. *Proc Biol Sci, 279*(1735), 2018-2024. doi:10.1098/rspb.2011.2358

Baxter, J. R., & Piazza, S. J. (2014). Plantar flexor moment arm and muscle volume predict torque-generating capacity in young men. *J Appl Physiol (1985), 116*(5), 538-544. doi:10.1152/japplphysiol.01140.2013

Benard, M. R., Becher, J. G., Harlaar, J., Huijing, P. A., & Jaspers, R. T. (2009). Anatomical information is needed in ultrasound imaging of muscle to avoid potentially substantial errors in measurement of muscle geometry. *Muscle Nerve, 39*(5), 652-665. doi:10.1002/mus.21287

Bertolotto, M., Perrone, R., Martinoli, C., Rollandi, G. A., Patetta, R., & Derchi, L. E. (1995). High resolution ultrasound anatomy of normal Achilles tendon. *Br J Radiol, 68*(813), 986-991. doi:10.1259/0007-1285-68-813-986

Biewener, A. A., & Roberts, T. J. (2000). Muscle and tendon contributions to force, work, and elastic energy savings: a comparative perspective. *Exerc Sport Sci Rev, 28*(3), 99-107.

Bobbert, M. F. (1990). Drop jumping as a training method for jumping ability. *Sports Med, 9*(1), 7-22.

Bobbert, M. F., Casius, L. J., Sijpkens, I. W., & Jaspers, R. T. (2008). Humans adjust control to initial squat depth in vertical squat jumping. *J Appl Physiol (1985), 105*(5), 1428-1440. doi:10.1152/japplphysiol.90571.2008

Bobbert, M. F., & Casius, L. J. R. (2005). Is the effect of a countermovement on jump height due to active state development? *Medicine & Science in Sports & Exercise, 37*(3), 440-446. doi:10.1249/01.mss.0000155389.34538.97

Bobbert, M. F., Gerritsen, K. G., Litjens, M. C., & Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height? *Med Sci Sports Exerc, 28*(11), 1402-1412.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1986). An estimation of power output and work done by the human triceps surae muscle-tendon complex in jumping. *J Biomech, 19*(11), 899-906.

Bobbert, M. F., Mackay, M., Schinkelshoek, D., Huijing, P. A., & van Ingen Schenau, G. J. (1986). Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol Occup Physiol, 54*(6), 566-573.

Bobbert, M. F., & van Zandwijk, J. P. (1999). Dynamics of force and muscle stimulation in human vertical jumping. *Med Sci Sports Exerc, 31*(2), 303-310.

Bojsen-Moller, J., Magnusson, S. P., Rasmussen, L. R., Kjaer, M., & Aagaard, P. (2005). Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *J Appl Physiol (1985), 99*(3), 986-994. doi:10.1152/japplphysiol.01305.2004

Bosco, C., & Komi, P. V. (1979). Potentiation of the mechanical behavior of the human skeletal muscle through prestretching. *Acta Physiol Scand, 106*(4), 467-472. doi:10.1111/j.1748-1716.1979.tb06427.x

Briggs, P. (2006). *Northern Tanzania: The Bradt Safari Guide with Kilimanjaro and Zanzibar.*: Bradt Travel Guides.

Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *J Electromyogr Kinesiol, 20*(6), 1023-1035. doi:10.1016/j.jelekin.2010.07.004

Butler, D. L., Grood, E. S., Noyes, F. R., & Zernicke, R. F. (1978). Biomechanics of ligaments and tendons. *Exerc Sport Sci Rev, 6*, 125-181.

Caia, J., Weiss, L. W., Chiu, L. Z., Schilling, B. K., Paquette, M. R., & Relyea, G. E. (2016). Do Lower-Body Dimensions and Body Composition Explain Vertical Jump Ability? *J Strength Cond Res, 30*(11), 3073-3083. doi:10.1519/JSC.0000000000001406

Cavagna, G. A., Citterio, G., & Jacini, P. (1975). Proceedings: The additional mechanical energy delivered by the contractile component of the previously stretched muscle. *J Physiol, 251*(1), 65P-66P.

Cavagna, G. A., Dusman, B., & Margaria, R. (1968). Positive work done by a previously stretched muscle. *J Appl Physiol, 24*(1), 21-32.

Choi, J. Y., Suh, J. S., & Seo, L. (2014). Salient features of the Maasai foot: analysis of 1,096 Maasai subjects. *Clin Orthop Surg, 6*(4), 410-419. doi:10.4055/cios.2014.6.4.410

Clarys, J. P., & Cabri, J. (1993). Electromyography and the study of sports movements: a review. *J Sports Sci, 11*(5), 379-448. doi:10.1080/02640419308730010

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res, 23*(1), 177-186. doi:10.1519/JSC.0b013e3181889324

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc, 42*(8), 1582-1598. doi:10.1249/MSS.0b013e3181d2013a

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 1- Biological basis of maximal power production. *Sports Med, 41*(1), 17-38. doi:10.2165/11537690-000000000-00000

Dahl, H. A., & Rinvik, E. (2010). *Menneskets funksjonelle anatomi*. Oslo: Cappelen akademisk.

Davis, D. S., Briscoe, D. A., Markowski, C. T., Saville, S. E., & Taylor, C. J. (2003). Physical characteristics that predict vertical jump performance in recreational male athletes. *Physical Therapy in Sport, 4*, 167-174.

Dawson, B., Fitzsimons, M., Green, S., Goodman, C., Carey, M., & Cole, K. (1998). Changes in performance, muscle metabolites, enzymes and fibre types after short sprint training. *Eur J Appl Physiol Occup Physiol, 78*(2), 163-169. doi:10.1007/s004210050402

De Luca, C. J. (1997). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics, 13*, 135-163.

De Luca, C. J., & Merletti, R. (1988). Surface myoelectric signal cross-talk among muscles of the leg. *Electroencephalogr Clin Neurophysiol, 69*(6), 568-575.

de Ruiter, C. J., Vermeulen, G., Toussaint, H. M., & de Haan, A. (2007). Isometric knee-extensor torque development and jump height in volleyball players. *Med Sci Sports Exerc, 39*(8), 1336-1346. doi:10.1097/mss.0b013e318063c719

Dietz, V., Schmidtbleicher, D., & Noth, J. (1979). Neuronal mechanisms of human locomotion. *J Neurophysiol, 42*(5), 1212-1222.

Dobbs, C. W., Gill, N. D., Smart, D. J., & McGuigan, M. R. (2015). Relationship between vertical and horizontal jump variables and muscular performance in athletes. *J Strength Cond Res, 29*(3), 661-671. doi:10.1519/JSC.0000000000000694

Dowling, J. J., & Vamos, L. (1993). Identification of kinetic and temporal factor related to vertical jump performance. *Journal of Applied Biomechanics, 9*, 95-110.

Edman, K. A., Elzinga, G., & Noble, M. I. (1978). Enhancement of mechanical performance by stretch during tetanic contractions of vertebrate skeletal muscle fibres. *J Physiol, 281*, 139-155.

Farina, D. (2006). Interpretation of the surface electromyogram in dynamic contractions. *Exerc Sport Sci Rev, 34*(3), 121-127.

Farina, D., Merletti, R., & Enoka, R. M. (2014). The extraction of neural strategies from the surface EMG: an update. *J Appl Physiol (1985), 117*(11), 1215-1230. doi:10.1152/japplphysiol.00162.2014

Fath, F., Blazevich, A. J., Waugh, C. M., Miller, S. C., & Korff, T. (2010). Direct comparison of in vivo Achilles tendon moment arms obtained from ultrasound and MR scans. *J Appl Physiol (1985), 109*(6), 1644-1652. doi:10.1152/japplphysiol.00656.2010

Fauth, M. L., Petushek, E. J., Feldmann, C. R., Hsu, B. E., Garceau, L. R., Lutsch, B. N., & Ebben, W. P. (2010). Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting. *J Strength Cond Res, 24*(4), 1131-1137. doi:10.1519/JSC.0b013e3181cc2353

Finni, T., Ikegawa, S., Lepola, V., & Komi, P. V. (2003). Comparison of force-velocity relationships of vastus lateralis muscle in isokinetic and in stretch-shortening cycle exercises. *Acta Physiol Scand, 177*(4), 483-491. doi:10.1046/j.1365-201X.2003.01069.x

Fukashiro, S., & Komi, P. V. (1987). Joint moment and mechanical power flow of the lower limb during vertical jump. *Int J Sports Med, 8 Suppl 1*, 15-21.

Fukashiro, S., Komi, P. V., Jarvinen, M., & Miyashita, M. (1995). In vivo Achilles tendon loading during jumping in humans. *Eur J Appl Physiol Occup Physiol, 71*(5), 453-458.

Fung, Y. C. (1967). Elasticity of soft tissues in simple elongation. *Am J Physiol, 213*(6), 1532-1544.

Gajdosik, R. L. (2001). Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clin Biomech (Bristol, Avon), 16*(2), 87-101.

Gheller, R. G., Dal Pupo, J., Ache-Dias, J., Detanico, D., Padulo, J., & dos Santos, S. G. (2015). Effect of different knee starting angles on intersegmental coordination and performance in vertical jumps. *Hum Mov Sci, 42*, 71-80. doi:10.1016/j.humov.2015.04.010

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol, 184*(1), 170-192.

Hara, M., Shibayama, A., Takeshita, D., & Fukashiro, S. (2006). The effect of arm swing on lower extremities in vertical jumping. *J Biomech, 39*(13), 2503-2511. doi:10.1016/j.jbiomech.2005.07.030

Hatze, H. (1998). Validity and reliability of methods for testing vertical jumping performance. *Journal of Applied Biomechanics, 14*, 127-140.

Hawkins, D., & Hull, M. L. (1990). A method for determining lower extremity muscle-tendon lengths during flexion/extension movements. *J Biomech, 23*(5), 487-494.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol, 10*(5), 361-374.

Hijikata, T., & Ishikawa, H. (1997). Functional morphology of serially linked skeletal muscle fibers. *Acta Anat (Basel), 159*(2-3), 99-107.

Hill, A. V. (1938). The heat of shortening and dynamics constants of muscles. *Proc R Soc Lond B Biol Sci, 126-B*, 136-195.

Hill, A. V. (1970). *First and Last Experiments in Muscle Mechanics*. Cambridge, UK: Cambridge University Press.

Hooke, R. (1678). *De Potentia Restituva, or Of Spring. Explaining the power of springing bodies*. London, England: Royal Society.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med, 30*(1), 1-15.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc, 41*(1), 3-13. doi:10.1249/MSS.0b013e31818cb278

Horowits, R., Kempner, E. S., Bisher, M. E., & Podolsky, R. J. (1986). A physiological role for titin and nebulin in skeletal muscle. *Nature, 323*(6084), 160-164. doi:10.1038/323160a0

Hruda, K. V., Hicks, A. L., & McCartney, N. (2003). Training for muscle power in older adults: effects on functional abilities. *Can J Appl Physiol, 28*(2), 178-189.

Ishikawa, M., Finni, T., & Komi, P. V. (2003). Behaviour of vastus lateralis muscle-tendon during high intensity SSC exercises in vivo. *Acta Physiol Scand, 178*(3), 205-213. doi:10.1046/j.1365-201X.2003.01149.x

Ishikawa, M., & Komi, P. V. (2007). The role of the stretch reflex in the gastrocnemius muscle during human locomotion at various speeds. *J Appl Physiol (1985), 103*(3), 1030-1036. doi:10.1152/japplphysiol.00277.2007

Ishikawa, M., & Komi, P. V. (2008). Muscle fascicle and tendon behavior during human locomotion revisited. *Exerc Sport Sci Rev, 36*(4), 193-199. doi:10.1097/JES.0b013e3181878417

Jaric, S. (2003). Role of body size in the relation between muscle strength and movement performance. *Exerc Sport Sci Rev, 31*(1), 8-12.

Jaric, S., Ristanovic, D., & Corcos, D. M. (1989). The relationship between muscle kinetic parameters and kinematic variables in a complex movement. *Eur J Appl Physiol Occup Physiol, 59*(5), 370-376.

Jones, G. M., & Watt, D. G. (1971). Observations on the control of stepping and hopping movements in man. *J Physiol, 219*(3), 709-727.

Jordania, J. (2011). *Why Do People Sing? Music in Human Evolution*: Logos.

Józsa, L., & Kannus, P. (1997). *Human tendons: Anatomy, physiology, and pathology.* Champaign: Human Kinetics.

Kannus, P. (2000). Structure of the tendon connective tissue. *Scand J Med Sci Sports, 10*(6), 312-320.

Kibele, A. (1998). Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *Journal of Applied Biomechanics, 14*, 105-117.

Kirby, T. J., McBride, J. M., Haines, T. L., & Dayne, A. M. (2011). Relative net vertical impulse determines jumping performance. *J Appl Biomech, 27*(3), 207-214.

Kirkendall, D. T., & Garrett, W. E. (1997). Function and biomechanics of tendons. *Scand J Med Sci Sports, 7*(2), 62-66.

Komi, P. V. (1990). Relevance of in vivo force measurements to human biomechanics. *J Biomech, 23 Suppl 1*, 23-34.

Komi, P. V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech, 33*(10), 1197-1206.

Komi, P. V., & Bosco, C. (1978). Utilization of stored elastic energy in leg extensor muscles by men and women. *Med Sci Sports, 10*(4), 261-265.

Kongsgaard, M., Nielsen, C. H., Hegnsvad, S., Aagaard, P., & Magnusson, S. P. (2011). Mechanical properties of the human Achilles tendon, in vivo. *Clin Biomech (Bristol, Avon), 26*(7), 772-777. doi:10.1016/j.clinbiomech.2011.02.011

Kraemer, W. J., & Newton, R. U. (2000). Training for muscular power. *Phys Med Rehabil Clin N Am, 11*(2), 341-368, vii.

Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc, 36*(4), 674-688.

Kubo, K., Kanehisa, H., Kawakami, Y., & Fukanaga, T. (2001). Growth changes in the elastic properties of human tendon structures. *Int J Sports Med, 22*(2), 138-143. doi:10.1055/s-2001-11337

Kubo, K., Kawakami, Y., & Fukunaga, T. (1999). Influence of elastic properties of tendon structures on jump performance in humans. *J Appl Physiol (1985), 87*(6), 2090-2096.

Kuitunen, S., Ogiso, K., & Komi, P. V. (2011). Leg and joint stiffness in human hopping. *Scand J Med Sci Sports, 21*(6), e159-167. doi:10.1111/j.1600-0838.2010.01202.x

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *J Appl Physiol (1985), 88*(3), 811-816.

Kwah, L. K., Pinto, R. Z., Diong, J., & Herbert, R. D. (2013). Reliability and validity of ultrasound measurements of muscle fascicle length and pennation in humans: a systematic review. *J Appl Physiol (1985), 114*(6), 761-769. doi:10.1152/japplphysiol.01430.2011

Lee, S. S., & Piazza, S. J. (2009). Built for speed: musculoskeletal structure and sprinting ability. *J Exp Biol, 212*(Pt 22), 3700-3707. doi:10.1242/jeb.031096

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *J Biomech, 37*(12), 1929-1940. doi:10.1016/j.jbiomech.2004.02.021

Levangie, P. K., & Norkin, C. C. (2011). *Joint Structure and Function: A Comprehensive Analysis. Fifth Edition*: F.A. Davis.

Lieber, R. L. (2002). *Skeletal Muscle Structure, Function and Plasticity: The Physiological Basis of Rehabilitation.* Philadelphia: Lippincott Williams & Wilkins.

Lieber, R. L., & Friden, J. (2000). Functional and clinical significance of skeletal muscle architecture. *Muscle Nerve, 23*(11), 1647-1666.

Lieber, R. L., & Friden, J. (2001). Clinical significance of skeletal muscle architecture. *Clin Orthop Relat Res*(383), 140-151.

Lundberg, A., Svensson, O. K., Nemeth, G., & Selvik, G. (1989). The axis of rotation of the ankle joint. *J Bone Joint Surg Br, 71*(1), 94-99.

MacIntosh, B., Gardiner, P., & McComas, A. (2006). *Muscle architecture and muscle fiber anatomy. In Skeletal muscle - Form and function.*: Human Kinetics.

Maganaris, C. N. (2002). Tensile properties of in vivo human tendinous tissue. *J Biomech, 35*(8), 1019-1027.

Maganaris, C. N., Baltzopoulos, V., & Sargeant, A. J. (1998). Changes in Achilles tendon moment arm from rest to maximum isometric plantarflexion: in vivo observations in man. *J Physiol, 510 (Pt 3)*, 977-985.

Maganaris, C. N., Baltzopoulos, V., & Sargeant, A. J. (2000). In vivo measurement-based estimations of the human Achilles tendon moment arm. *Eur J Appl Physiol, 83*(4 -5), 363-369. doi:10.1007/s004210000247

Maganaris, C. N., Baltzopoulos, V., & Tsaopoulos, D. (2006). Muscle fibre length-to-moment arm ratios in the human lower limb determined in vivo. *J Biomech, 39*(9), 1663-1668. doi:10.1016/j.jbiomech.2005.04.025

Maganaris, C. N., & Paul, J. P. (1999). In vivo human tendon mechanical properties. *J Physiol, 521 Pt 1*, 307-313.

Manson, S. A., Brughelli, M., & Harris, N. K. (2014). Physiological characteristics of international female soccer players. *J Strength Cond Res, 28*(2), 308-318. doi:10.1519/JSC.0b013e31829b56b1

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *J Strength Cond Res, 18*(3), 551-555. doi:10.1519/1533-4287(2004)18<551:RAFVOS>2.0.CO;2

Markovic, G., & Jaric, S. (2004). Movement performance and body size: the relationship for different groups of tests. *Eur J Appl Physiol, 92*(1-2), 139-149. doi:10.1007/s00421-004-1076-7

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011a). Markers of postmatch fatigue in professional Rugby League players. *J Strength Cond Res, 25*(4), 1030-1039. doi:10.1519/JSC.0b013e3181cc22cc

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011b). The role of rate of force development on vertical jump performance. *J Strength Cond Res, 25*(2), 379-385. doi:10.1519/JSC.0b013e3181be305c

Myllyharju, J., & Kivirikko, K. I. (2001). Collagens and collagen-related diseases. *Ann Med, 33*(1), 7-21.

Nordin, M., & Frankel, V. H. (2001). *Basic Biomechanics of the Musculoskeletal System*. Philadelphia: Lippincott Williams & Wilkins.

Orr, J. B., & Gilks, J. L. (1931). Studies of nutrition: the physique and health of two African tribes. Medical Research Council. *Special Report Series*(19), 1-93.

Podolsky, R. J., & Shoenberg, M. (1983). *Force generation and shortening in skeletal muscle. In L. D.Peachey, R. H. Adrian, & S. R. Geiger (Eds.)*. Baltimore, MD: American Physiolgical Society.

Roberts, T. J. (2002). The integrated function of muscles and tendons during locomotion. *Comp Biochem Physiol A Mol Integr Physiol, 133*(4), 1087-1099.

Rosager, S., Aagaard, P., Dyhre-Poulsen, P., Neergaard, K., Kjaer, M., & Magnusson, S. P. (2002). Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports, 12*(2), 90-98.

Raastad, T., Paulsen, G., Refsnes, P. E., Rønnestad, B. R., & Wisnes, A. (2010). *Styrketrening - I teori og praksis*. Oslo: Gyldendal.

Sano, K., Ishikawa, M., Nobue, A., Danno, Y., Akiyama, M., Oda, T., . . . Komi, P. V. (2013). Muscle-tendon interaction and EMG profiles of world class endurance runners during hopping. *Eur J Appl Physiol, 113*(6), 1395-1403. doi:10.1007/s00421-012-2559-6

Sano, K., Nicol, C., Akiyama, M., Kunimasa, Y., Oda, T., Ito, A., . . . Ishikawa, M. (2015). Can measures of muscle-tendon interaction improve our understanding of the superiority of Kenyan endurance runners? *Eur J Appl Physiol, 115*(4), 849-859. doi:10.1007/s00421-014-3067-7

Scholz, M. N., Bobbert, M. F., van Soest, A. J., Clark, J. R., & van Heerden, J. (2008). Running biomechanics: shorter heels, better economy. *J Exp Biol, 211*(Pt 20), 3266-3271. doi:10.1242/jeb.018812

Seynnes, O. R., de Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol (1985), 102*(1), 368-373. doi:10.1152/japplphysiol.00789.2006

Seynnes, O. R., Maganaris, C. N., de Boer, M. D., di Prampero, P. E., & Narici, M. V. (2008). Early structural adaptations to unloading in the human calf muscles. *Acta Physiol (Oxf), 193*(3), 265-274. doi:10.1111/j.1748-1716.2008.01842.x

Sheppard, J. M., Cronin, J. B., Gabbett, T. J., McGuigan, M. R., Etxebarria, N., & Newton, R. U. (2008). Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *J Strength Cond Res, 22*(3), 758-765. doi:10.1519/JSC.0b013e31816a8440

Stafilidis, S., & Arampatzis, A. (2007). Muscle - tendon unit mechanical and morphological properties and sprint performance. *J Sports Sci, 25*(9), 1035-1046. doi:10.1080/02640410600951589

Stone, M. H., Sanborn, K., O'Bryant, H. S., Hartman, M., Stone, M. E., Proulx, C., . . . Hruby, J. (2003). Maximum strength-power-performance relationships in collegiate throwers. *J Strength Cond Res, 17*(4), 739-745.

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining countermovement jump height with the impulse method. *Journal of Applied Biomechanics, 17*, 43-54.

Thomas, J., Nelson, J., & Silverman, S. (2011). *Research methods in physical activity*. Champaign, USA: Human Kinetics.

Thorlund, J. B., Michalsik, L. B., Madsen, K., & Aagaard, P. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scand J Med Sci Sports, 18*(4), 462-472. doi:10.1111/j.1600-0838.2007.00710.x

van Ingen Schenau, G. J. (1984). An alternative view of the concept of utilization of elastic energy in human movements. *Hum. Mov. Sci., 3*, 301-336.

Vanezis, A., & Lees, A. (2005). A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics, 48*(11-14), 1594-1603. doi:10.1080/00140130500101262

Viidik, A. (1973). Functional properties of collagenous tissues. *Int Rev Connect Tissue Res, 6*, 127-215.

Wang, J. H., Guo, Q., & Li, B. (2012). Tendon biomechanics and mechanobiology--a minireview of basic concepts and recent advancements. *J Hand Ther, 25*(2), 133-140; quiz 141. doi:10.1016/j.jht.2011.07.004

Wickiewicz, T. L., Roy, R. R., Powell, P. L., & Edgerton, V. R. (1983). Muscle architecture of the human lower limb. *Clin Orthop Relat Res*(179), 275-283.

Wilson, J. M., Loenneke, J. P., Jo, E., Wilson, G. J., Zourdos, M. C., & Kim, J. S. (2012). The effects of endurance, strength, and power training on muscle fiber type shifting. *J Strength Cond Res, 26*(6), 1724-1729. doi:10.1519/JSC.0b013e318234eb6f

Yamaguchi, G. T. (2001). *Dynamic Modeling of Musculoskeletal System*. MA, USA: Kluwer Academic Publishers.

Zatsiorsky, V., & Prilutsky, B. (2012). *Biomechanics of skeletal muscles. Champaign: Human Kinetics.*: Champaign: Human Kinetics.

Ziv, G., & Lidor, R. (2010). Vertical jump in female and male basketball players--a review of observational and experimental studies. *J Sci Med Sport, 13*(3), 332-339. doi:10.1016/j.jsams.2009.02.009

Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A. M., Wagner, A., Magnusson, S. P., . . . Simonsen, E. B. (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol, 534*(Pt. 2), 613-623.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol (1985), 93*(4), 1318-1326. doi:10.1152/japplphysiol.00283.2002

Overview of figures

Appendix

1: Article

2: Full experimental protocol

3: Written informed consent form

4: Ethics approval

Appendix 1: Article

MAXIMAL JUMP PERFORMANCE IN MAASAI JUMPERS AND CAUCASIAN CONTROLS

Refsdal, A. S., Bojsen-Møller, J., Seynnes, O. R., Jakobsen, V., Hernæs, H., Magnusson, S. P., Aagaard, P. & Christensen, D. L.

Norwegian School of Sport Sciences

Corresponding author:
Andreas Skiri Refsdal

Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

Telephone: +4747627373
E-mail: andreasrefsdal@gmail.com

Co-authors:

Jens Bojsen-Møller, Olivier Seynnes, Vidar Jakobsen, Herman Hernæs, Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

Stig Peter Magnusson, Department of Clinical Medicine, Bispebjerg Hospital, Copenhagen, Denmark

Per Aagaard, Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

Dirk Lund Christensen, Section of Global Health, University of Copenhagen, Copenhagen, Denmark

ABSTRACT

Purpose. *The purpose of the present thesis was to investigate countermovement jump (CMJ) performance, muscle-tendon morphology and anthropometrics in Tanzanian Maasai individuals and to compare these data to Caucasian controls.*

Methods. *28 healthy subjects (Maasai = 20, Caucasian = 8) volunteered for the study. Maximal CMJ performance was evaluated by use of force plate kinetics and kinematics. Timing of muscle activation was examined with electromyography (EMG). Moreover, anthropometric data for the lower leg was acquired, and muscle architecture and tendon dimensions were assessed by use of ultrasound (US). Finally, jump height and joint angles were estimated for the Maasai while performing a traditional 'jump dance ritual'.*

Results. *Relative to body height the Maasai had greater foot ($P < 0.001$) and hallux length ($P = 0.019$). The Maasai had shorter lower legs compared to the Caucasians in absolute values ($P = 0.033$) and displayed shorter fascicles and lower muscle thickness for gastrocnemius (GM) and vastus lateralis (VL) both in absolute (GM fascicle length: $P < 0.001$, VL fascicle length: $P < 0.001$, GM thickness: $P < 0.001$, VL thickness: $P < 0.001$) and relative values (GM fascicle length: $P < 0.001$, VL fascicle length: $P = 0.002$, GM thickness: $P < 0.001$, VL thickness: $P = 0.003$). Achilles tendon (AT) aponeurosis length was greater in the Maasai compared to the controls both in absolute ($P = 0.042$) and relative values ($P = 0.005$). Relative to body height AT and AT moment arm length were significantly greater for the Maasai (AT length: $P = 0.014$, AT moment arm: $P = 0.017$). CMJ hip flexion was significantly greater ($P < 0.001$) in the control group. Jump height in CMJ were significantly lower for the Maasai in absolute values (Maasai: 33.3 ± 6.6 cm vs. Caucasian: 40.0 ± 4.9 cm, $P = 0.015$), but relative to body weight (BW) jump height was greater in the Maasai group (Maasai: 0.6 ± 0.1 vs. Caucasian: 0.5 ± 0.1, $P = 0.009$). Duration of the braking and push-off phases were significantly ($P < 0.001$) in the Maasai subjects compared to the Caucasian controls. The EMG-data demonstrated overall 'wider' signals for the Maasai group compared to the controls. For 18 Maasai subjects, average jump height during a so-called 'jump dance ritual' was 46 cm. Jump height during the 'jump dance ritual' correlated positively to BW ($r = 0.68$) and CMJ height ($r = 0.69$).*

Conclusion. *The Maasai subjects jumped higher in maximal CMJ compared to Caucasian controls when adjusting for BW, and practiced a more upright jumping strategy compared to the controls. In maximal CMJ, the time duration of the braking and push-off phases were shorter for the Maasai subjects. Fascicle length and muscle thickness were less in GM and VL for the Maasai group both in absolute and relative values. The Maasai subjects had a longer AT, AT aponeurosis and AT moment arm relative to body height compared to the controls. Furthermore, jump height during the 'jump dance ritual' for the Maasai was remarkable and close to 50 cm. The present study is the first to incorporate precise biomechanical methodology to investigate jumping performance in Maasai individuals, and the results underscore previous notions that the Maasai show good jump performance. The study demonstrates clear differences in anthropometry between groups and combined with the Maasai lifestyle (consisting of traditional jumping rituals and a high volume of daily activity) it sheds light on the factors that underlie the impressive jumping capabilities in Maasai individuals. The Maasai possess significant jumping performance despite no specific strength or plyometric training history as common in western world jumping athletes.*

Keywords: Maasai, jump performance, CMJ, muscle, EMG.

Abbreviations

AT	Achilles Tendon
BMI	Body Mass Index
BW	Body Weight
CMJ	Countermovement Jump
EMG	Electromyography
GM	Gastrocnemius Medialis
MTU	Muscle-Tendon Unit
MVC	Maximal Voluntary Contraction
RFD	Rate of Force Development
SD	Standard Deviation
SOL	Soleus
SSC	Stretch-Shortening Cycle
TA	Tibialis Anterior
US	Ultrasound
VJ	Vertical Jumping
VL	Vastus Lateralis

INTRODUCTION

The Maasai people are an ethnic group of semi-nomadic people inhabiting the southern part of Kenya and northern part of Tanzania where they settled a few hundred years ago according to their own history. They essentially came from Nilotic tribes that moved south from Sudan, and then integrated with the Cushitic tribes, which merged the traditions from both groups. The Maasai are well known for their characteristic clothing and customs, in addition to their traditional rituals involving dancing, chanting and repetitive jumping. The jumping tribe rituals are a part of a centuries long tradition that involves a large number of jumps performed over 2-3 days by young male Maasai individuals known as the Morani (15-35 years of age).

Jumping is a natural, but at the same time a relatively advanced type of human movement that requires complex coordination skills between the contractile elements of the upper- and lower-body segments (Markovic, Dizdar, Jukic, & Cardinale, 2004; Sheppard et al., 2008). Preliminary observations by Dirk Lund Christensen (personal communication) suggested jump heights of more than 50 cm during the repetitive Maasai jumping which is similar to maximal countermovement jump (CMJ) performance in elite jumping athletes in the western world (de Ruiter, Vermeulen, Toussaint, & de Haan, 2007). Jump performance in Maasai individuals remain anecdotal as no previous studies have in detail measured jump performance in the Maasai. Furthermore, precise measurement of kinematics and kinetics have not previously been conducted. In addition, existing information about anthropometrical data on the Maasai people is limited, although, one previous study has examined the Maasai foot (Choi, Suh, & Seo, 2014).

The impressive jump performance of the Maasai people could be explained by several factors, but most likely frequent jumping throughout the lifespan and starting from an early age plays a significant role. On our field trip to Tanzania several Maasai individuals reported that they had done regular jumping since approximately five years of age. It is important to state that this remains an approximation, as most Maasai are unaware of their actual biological age. Nonetheless, it seems well established that the Maasai lifestyle, culture and tradition imposes a remarkable specific training load on muscles and tendons, which consequently may influence performance in maximal jumping tasks.

Anthropometric features could also play a role for the superior Maasai jump performance. Kenya is well known for their great athlete runners, especially from the Kalenjin tribe, and both Kenyans and the Maasai people are part of the east African population. Recent studies have reported that Kenyan runners display anthropometrical features of muscle and tendon in the lower leg e.g. longer Achilles tendon (AT) and lower gastrocnemius medialis (GM) pennation angle that enables them to utilize energy efficiently during stretch-shortening cycle (SSC) movements (Sano et al., 2013; Sano et al., 2015). The efficient utilization of elastic energy combined with a greater jump height during repetitive jumps in Kenyan runners have been explained by a high recoil from tendinous tissues (Sano et al., 2013). Hence, it may be assumed that also Maasai subjects obtain and benefit from specific anthropometrical features that contribute to jump performance.

Purpose and hypothesis. No previous studies have incorporated precise biomechanical methodology to investigate vertical jumps (VJ) in the Maasai. Therefore, one feasible strategy to increase knowledge about aspects of human performance in VJ would be to examine that of Maasai individuals. The purpose of the present study was thus to investigate CMJ performance, muscle-tendon morphology and anthropometrics in Tanzanian Maasai individuals and to compare these to Caucasian controls. It was hypothesized that the Maasai individuals displayed distinctive anthropometrical features (e.g. a longer AT moment arm and shorter fascicles) and a significant jump performance.

MATERIAL AND METHODS

This study is part of a larger investigation on the Maasai people administered and funded by the Norwegian School of Sport Sciences, the University of Southern Denmark, Institute of Sports Medicine Copenhagen at Bispebjerg Hospital and the University of Copenhagen. Principal investigator of the overall study is Associate Professor Dirk Lund Christensen (Section of Global Health, University of Copenhagen). The study was in part funded by the Danish Ministry of Culture.

Study design. The present study was an experimental non-invasive study investigating anthropometrics, maximal jumping and the traditional Maasai 'jump dance ritual' comparing Maasai jumpers and Caucasian controls.

Subjects. A total of 28 subjects volunteered for the study; Maasai (n=20) and Caucasian (n=8). The Maasai subjects (age: 26.5 ± 6.0 yr, height: 170.1 ± 7.0 cm, weight: 55.8 ± 6.7 kg) were recruited through local project collaborators in the Monduli region of Tanzania. Norwegian subjects (age: 23.4 ± 2.4 yr, height: 183.5 ± 5.9 cm, weight: 85.0 ± 10.3 kg) were recruited through oral and written communications at the Norwegian School of Sport Sciences. Inclusion criteria were male subjects between 18-40 years of age without any injuries and with the ability to perform the relevant protocol. Maasai subjects were young athletic males (Maasai jumpers) from traditional Maasai communities in the outskirts of Monduli in the Arusha Region of Tanzania. As the Caucasian controls were recreationally active in mainly strength training they were told to restrain from heavy strength training 24 hours prior to testing.

The study included only previously used and safe non-invasive methods, and the risk of injury related to testing was therefore considered minimal. The study was conducted in accordance with the guidelines of the Declaration of Helsinki and was examined by relevant ethics committees in Tanzania. In addition, all subjects were informed that they were allowed to withdraw from the study at any time and without any special reason.

Protocol overview. Anthropometric measures were taken prior to jump testing. CMJ were performed on a force plate from an upright standing position with arms akimbo to minimize any influence from the arms. The subjects kept their feet parallel at a distance equal to the width of their shoulders. Following a signal from the test-leader, the subjects made a rapid downward movement by flexing their hip, knees and ankles and then immediately jumped as high as possible. The subjects were generally instructed to jump as high and as fast as possible and otherwise use their preferred jumping technique. During the subsequent Maasai ‘jump dance ritual’ testing, the subjects (only Maasai) were instructed to jump as close to their normal ritual despite the somewhat awkward situation of being in the lab. Subjects were allowed to carry both their stick, knife and full clothing while jumping, and a group of Maasai were chanting and dancing close by to resemble the jumping ceremony. It was thus not possible to attach reflective markers to their lower extremities however, one marker was attached to the acromion. The force plate was positioned in the middle of the test area, and all subjects were lined up in order to jump. Each subject completed a few repetitive maximal jumps on the force plate, one at a time.

Anthropometrics. Body height was measured in a standing position to the nearest 0.1 cm with a portable stadiometer (Meterex II, D97, UNICEF, Copenhagen, Denmark). Body weight (BW) was measured to the nearest 0.1 kg with a portable high precision scale (BWB-800 SMA, Tanita, Tokyo, Japan). AT length was measured with the subjects lying prone on a bench with the feet over the edge (mid shank) to ensure a neutral ankle joint position. A LogicScan 128 US-system (EXT-1Z, Telemed, Lithuania), including a linear 60 mm transducer (HL9.0/60/128Z-2, Telemed, Lithuania) with a scanning frequency of 12 MHz was used to locate the insertion of the AT on the calcaneus. The probe was moved proximally to the most distal insertion of soleus (SOL) on the AT. Both points were marked with a pen, and the distance was measured externally and taken to represent the free AT length. The AT aponeurosis length was determined by moving the US-probe proximally to identify the most distal insertion of the GM on the AT, which was marked with a pen and subsequently the distance from the SOL insertion to the GM insertion was measured thus identifying the aponeurosis length (Stafilidis & Arampatzis, 2007). US-images of the resting muscle architecture (muscle thickness and fascicle pennation angle) were acquired at the largest part of the muscle bellies (approximately at the lower 30% of muscle length in GM and 40% for the vastus laterlis (VL)) (Abe, Kumagai, & Brechue, 2000; De Luca, 1997).

To calculate foot length, hallux length and AT moment arm, a custom-built measurement board was used (Scholz, Bobbert, van Soest, Clark, & van Heerden, 2008) (Figure 1). The subjects were instructed to stand upright on the board aligning the lateral and subsequently the medial part of the right foot with the edge of the plate. The tip of both the lateral and medial malleoli and the tip of the first metatarsal were marked with a pen. Digital images were taken of the foot medially and laterally with different centers of the photo to minimize image distortion. Lower leg circumference was measured at 10% increments of the lower leg using a measuring tape. Lower leg length was defined as the distance from the tip of the lateral malleolus to the lateral epicondyle of femur, while upper leg length was defined as the distance from the lateral epicondyle of femur to the trochanter major. Anatomical landmarks were identified by palpation.

AT moment arm, foot length and hallux length was calculated from images using ImageJ (National Institutes of Health, Maryland, USA). AT moment arm was considered as the average value of the distance between the tip of the medial and lateral malleolus to the most posterior aspect of the AT (Sano et al., 2015; Scholz et al., 2008). Foot length was determined as the distance between the most posterior point of the heel and the most anterior point of the hallux. Furthermore, hallux length was defined as the distance between the most prominent aspect of the first metatarsal and the most anterior point of the hallux. Resting muscle architecture was calculated from US-images using ImageJ. To ensure an accurate measurement fascicle length (minimal out-of-plane error), the US-probe was aligned with the muscle fascicles (Benard, Becher, Harlaar, Huijing, & Jaspers, 2009). Both resting fascicle length and resting pennation angle was calculated three times from the same image for each subject and then averaged. Relative lower leg circumference was calculated as the percentage of the greatest individual circumference for each measuement site.

Figure 1: *Lateral and medial view of the right foot of a Maasai subject standing upright on the custom-built measurement board. The AT moment arm was calculated from the average of medial and lateral images by measuring the horizontal distance from the malleoli to the posterior aspect of the AT. Foot length was calculated from the medial view images. Hallux length was calculated from medial view images with the hallux in center of the image.*

Kinetics. Caucasian subjects completed the jump tests on an AMTI BP6001200 force plate (AMTI, Watertown, MA, USA) leveled to the ground. Data from the Maasai subjects were captured on a custom-built force plate fabricated in a lightweight design (Biomekanikk AS, Oslo, Norway). As the force plate could not be lowered into the ground in Tanzania, a lightweight frame of plywood and Styrofoam surrounded the plate to minimize the risk of injury (Figure 2). Sampling frequency was set to 300 Hz. All recorded analog kinetic data were sent to an USB analog board (S/N 8161, Qualisys, AB, Gothenburg, Sweden), converted to digital signals and finally exported to the motion analysis software Qualisys Track Manager (Qualisys, AB, Gothenburg, Sweden). Timeframes of three Oqus 400 cameras (Qualisys, AB, Gothenburg, Sweden) were matched to the USB analog board using a sync cable.

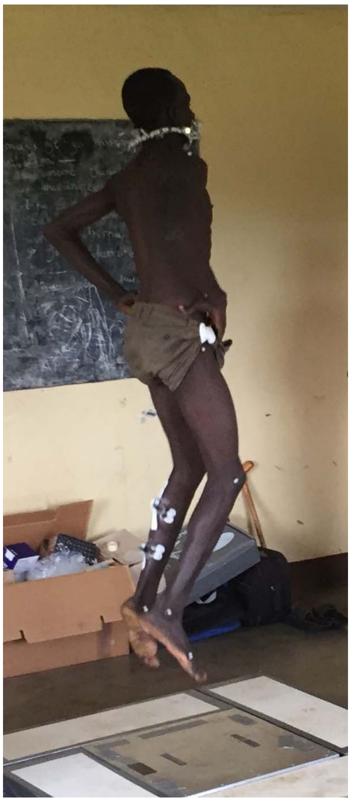


Figure 2: *Maasai during the CMJ flight phase. The light-weight force plate including the plywood and Styrofoam frame can be seen in the lower portion of the image. Placement of the reflective markers is visible on the right side of the subject.*

All subjects performed 3-5 CMJ, were the highest jump was selected for statistical analysis (Thorlund, Michalsik, Madsen, & Aagaard, 2008). Force data was filtered with a Butterworth second-order low-pass filter (cut-off frequency 100 Hz). The impulse-method was used to estimate jump height, where net vertical force acting on the jumper prior to takeoff was integrated in order to estimate takeoff velocity. Takeoff velocity was later used in a projectile motion equation to determine jump height (Anderson & Pandy, 1993). Maximal force was determined from the force signal and maximal power was calculated as the product of force and velocity. Rate of force development (RFD) was calculated as the average tangential slope at 0-100 ms relative to the start of the eccentric deceleration phase (return of body mass) (Thorlund et al., 2008). The onset of jump was determined as the time point where the mass of the subject was 5 N below mody mass and take off was identified as the time point where the ground reaction force reached below 40 N (Street, McMillan, Board, Rasmussen, & Heneghan, 2001).

'Jump dance ritual' jump height was calculated as the difference between the vertical position of the reflective acromion marker in the neutral standing position and the highest point of the jump. A 701.6 mm wand-stick was used as a reference length within the obtained video.

Kinematics. Kinematic data were obtained two-dimensionally from reflective markers placed on six different anatomical landmarks (acromion, trochanter major, lateral epicondyle of femur, lateral malleolus, calcaneus and fifth metatarsal) using three Oqus 400 cameras. Markers had a diameter of 12 mm, and identification of the anatomical landmarks was made by palpation. Sampling frequency was set to 300 Hz. Calibration of the recorded area was done using a reference frame on the force plate, and a calibration-wand. Motion data was exported directly to the Qualisys Track Manager.

During Maasai 'jump dance ritual' testing, only one reflective marker at the acromion were attached to each subject. A smartphone (Apple iPhone 6, Apple, Cupertino, USA) recorded video in the sagittal plane at 240 fps for post-hoc manual analysis of jump height and joint-angles of the ankle, knee and hip. A video tracking software was used for the analysis (Tracker, Video Analysis and Modeling Tool, Open Source Physics).

Position data were low-pass filtered (Butterworth second-order with a cut-off frequency of 5 Hz). Joint angles were calculated from the position of three markers for each joint: Ankle joint angle; lateral epicondyle, lateral malleolus and fifth metatarsal. Knee joint angle; trochanter major, lateral epicondyle and lateral malleolus. Hip joint angle; acromion, trochanter major and lateral epicondyle. Length of GM muscle-tendon unit (MTU) was calculated using the following formula (Hawkins & Hull, 1990):

$$L = C0 + C1\alpha + C2\beta + C3\beta^2 + C4\phi$$

$$GM\ MTU\ length = 0.900 + 0\alpha - 6.20E\text{-}4\beta + 0\beta^2 + 2.14E\text{-}3\phi$$

(α, β, φ represents hip, knee, and ankle joint angles at any given time)

As only one reflective marker was used while performing the traditional 'jump dance ritual', the analysis was done manually: Videos were examined frame by frame, extracting still images from the bottom position of each jump. A total of 337 jumps were analyzed. Only full cycle jumps were used in the results, eliminating the first takeoff and last landing of each jump cycle. Ankle, knee and hip angles were determined manually by use of digital imaging software (ImageJ). Approximately the same anatomical landmarks as described in the previous paragraph were used (Figure 3).

Figure 3: *Estimation of joint angles (ankle, knee and hip) in the bottom position of a jump during the traditional Maasai 'jump dance ritual'.*

Electromyography. Surface electromyography (EMG) was sampled from the left leg VL, GM, SOL and tibialis anterior (TA) using bipolar surface electrodes (Neuroline 720 72000-S, Ambu, Ballerup, Denmark) (electrode material: Ag/AgCl, size: 45 x 22 mm) with an inter-electrode distance of 20 mm. Signals were sent from a wireless transmitter (Noraxon DTS EMG, Noraxon Inc., Scottsdale, AZ, USA) to a receiver (Noraxon TeleMyo DTS Desk Receiver, Noraxon Inc., Scottsdale, AZ, USA) connected to a computer. Electrodes were placed according to SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) project (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Prior to electrode placement the skin was shaved and cleaned with ispropanol to reduce skin impedance. Sampling frequency was set to 1500 Hz, and EMG-data were exported directly to the Qualisys Track Manager. EMG-data was first band-pass filtered (10-500 Hz) before filtering with a Butterworth second-order low-pass filter. As the Maasai were unfamiliar with maximal voluntary contractions (MVC), unfortunately no maximal EMG-data could be reliably obtained. Therefore the analysis of EMG-data was limited to timing patterns of muscle activation during CMJ. Relative EMG was thus based on peak values obtained during maximal jumps for each subject (ranging from 0-100%).

Corrections to body size. Based on dimensional theory (Jaric, 2003; Markovic & Jaric, 2004), data were expressed both in absolute and relative values using allometric parameters. The equation P/BW^{ap} (BW = body weight, and ap = allometric parameter) was used to obtain the normalized value.

Statistics. Differences between groups were analyzed using an independent samples t-test. The overall alpha level was set to $P \leq 0.05$ for determination of statistical differences for all tests. To determine the relation between relevant parameters, linear regression analysis was performed using the Pearson product moment correlation coefficient (r) (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analyses were performed in IBM SPSS Statistics 24 (International Business Machines, Armonk, New York, USA. Results are reported as means ± standard deviation (SD) unless otherwise stated.

Validity and reliability. When applying the impulse-method with a force plate sampling frequency of 300 Hz, the combined maximal potential error is approximately 2% (Street et al., 2001). Furthermore, previous investigations have observed a coefficient of determination of r2 = 0.81-0.98 and a coefficient of variation of 12.6% (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005). Both validity and reliability are reported to be good for US measurements of muscle thickness, fascicle length and fascicle pennation angle (Ishikawa & Komi, 2007; Kwah, Pinto, Diong, & Herbert, 2013; Seynnes, Maganaris, de Boer, di Prampero, & Narici, 2008). Moreover, surface EMG is considered a valid and reliable method for measuring muscle activation in leg muscles during motion (Fauth et al., 2010).

RESULTS

Anthropometrics. No difference was seen in age, but the Caucasian subjects had a greater BW ($P < 0.001$) and height ($P < 0.001$) compared to the Maasai. Consequently, the body mass index (BMI) of the controls was significantly higher ($P < 0.001$). Foot length and hallux length did not differ in absolute values, but relative to body height the Maasai had greater foot ($P < 0.001$) and hallux length ($P = 0.019$). The Maasai had shorter lower legs compared to the controls in absolute values ($P = 0.033$), but related to body height the lower leg length was similar. There was no significant difference in thigh or whole leg length between groups, although thigh length had a tendency to be greater ($P = 0.051$) for the Maasai relative to body height (Table 1).

Muscle architecture. A statistically significant difference was found between groups for both fascicle length (GM absolute: $P < 0.001$, GM relative: $P < 0.001$, VL absolute: $P < 0.001$, VL relative: $P = 0.002$) and muscle thickness (GM absolute: $P < 0.001$, GM relative: $P < 0.001$, VL absolute: $P < 0.001$, VL relative: $P = 0.003$), such that the Maasai displayed shorter fascicles and lower muscle thickness both in absolute and relative values. No difference was observed in muscle fiber pennation angle between groups (Table 2).

Tendon morphology. Free AT length was shorter for the Maasai subjects in absolute values ($P = 0.035$), but no significant difference was found when tendon length was related to body height. AT aponeurosis length was greater in the Maasai compared to Caucasian both in absolute ($P = 0.042$) and relative values ($P = 0.005$). AT length and AT moment arm did not differ between groups in absolute values, but relatively these values were significantly greater for the Maasai (AT length: $P = 0.014$, AT moment arm: $P = 0.017$) (Table 3 & Figure 4).

Lower leg circumference. All lower leg circumference measurements were significantly lower ($P < 0.001$) in Maasai subjects compared to the Caucasian group (absolute values) (Figure 5). When related to lower leg length and maximal circumference, the data demonstrated a more proximal distribution of muscles in the Maasai compared to the controls (Figure 6). The data thus implied that Maasai subjects had shorter muscles and a tendency to larger leg circumference just proximal to the ankle joint compared to that of the Caucasian subjects (Figure 5 & 6).

CMJ. The EMG-data demonstrated overall 'wider' signals for the Maasai group compared to the controls (Figure 7 & 8). Ankle and knee joint angles were similar between groups, but hip flexion was significantly greater ($P < 0.001$) in the Caucasian group (Figure 7, 8 & Table 5). The entire jump phase duration was considerably shorter, and the force rise was faster for the Maasai subjects compared to the controls. Maasai subjects produced a higher maximal force relative to BW compared to the controls, but the force drop was similarly faster (Figure 8, 9 & Table 4).

Jump height in CMJ were significantly lower for the Maasai in absolute values (Maasai: 33.3 ± 6.6 cm vs. Caucasian: 40.0 ± 4.9 cm, $P = 0.015$), but relative to BW jump height was greater in the Maasai group (Maasai: 0.6 ± 0.1 vs. Caucasian: 0.5 ± 0.1, $P = 0.009$) (Table 4). Net impulse and maximal power were less for the Maasai subjects in both absolute (net impulse: $P < 0.001$, maximal power: $P < 0.001$) and relative values (net impulse: $P < 0.001$, maximal power: $P = 0.011$). There were no significant differences between groups for maximal force in the braking phase. The maximal force in the push-off phase was lower for the Maasai subjects (absolute values) ($P = 0.015$), but did not differ between groups relative to BW (Table 4). Lower leg stiffness was positively correlated to RFD at 100 ms relative to BW for both the Maasai and Caucasian group (Maasai: $r = 0.90$, $P < 0.001$, Caucasian: $r = 0.90$, $P = 0.002$) (Figure 10). Duration of the braking and push-off phases were significantly shorter ($P < 0.001$) in Maasai subjects compared to the controls. No difference was found in duration of the unweighting phase (Figure 11).

Jump dance ritual. For 18 Maasai subjects, average 'jump dance ritual' jump height was 46 cm (Table 6). Absolute joint angles in bottom position were: ankle = 57°, knee = 98° and hip = 100° (Figure 12). Jump height in the 'jump dance ritual' positively related to BW ($r = 0.68$) (Figure 13). Additionally, jump height in CMJ were positively correlated to jump height in the 'jump dance ritual' ($r = 0.69$) (Figure 14).

Table 1. Anthropometrics: *Age (yr), height (cm), BW (kg) and BMI (kg/m^2) in absolute values. Foot length (cm), hallux length (cm), lower leg length (LLL), upper leg length (ULL) and whole leg length (WLL) in absolute values (cm) and relative to body height (%) for the Maasai and Caucasian group. Values are means ± SD.*

Variable	Maasai (n=20)	Caucasian (n=8)	P-value
Age (yr)	26.5 ± 6.0	23.4 ± 2.4	0.167
Height (cm)	170.1 ± 7.0**	183.5 ± 5.9	<0.001
Weight (kg)	55.8 ± 6.7**	85.0 ± 10.3	<0.001
BMI (kg/m^2)	19.3 ± 1.7**	25.2 ± 2.6	<0.001
Foot length (cm)	26.0 ± 1.4	26.1 ± 1.0	0.968
Foot length/h (%)	15.3 ± 0.6**	14.2 ± 0.5	<0.001
Hallux length (cm)	69.1 ± 7.2	68.2 ± 3.1	0.738
Hallux length/h (%)	4.1 ± 0.4*	3.7 ± 0.1	0.019
LLL (cm)	42.8 ± 3.2*	45.6 ± 2.0	0.033
LLL/h (%)	25.2 ± 1.1	24.8 ± 0.6	0.418
ULL (cm)	41.3 ± 2.4	42.8 ± 3.0	0.166
ULL/h (%)	24.3 ± 0.9	23.4 ± 1.5	0.051
WLL (cm)	84.1 ± 5.2	88.4 ± 4.5	0.054
WLL/h (%)	49.4 ± 1.7	48.2 ± 1.8	0.096

*,** Statistically significant difference between groups (P ≤ 0.05 and P ≤ 0.001, respectively).

Table 2. Muscle architecture: *GM and VL resting fascicle length (rFa) in mm and relative to LLL/ULL (%), thickness in mm and relative to BW using an allometric parameter (P/BM$^{0.33}$) and resting pennation angle (°) (rPa) for the Maasai and Caucasian group. Values are means ± SD. (For the Maasai group n=19 for VL thickness.)*

Variable	Maasai (n=20)	Caucasian (n=8)	P-value
GM rFa (mm)	48.9 ± 6.3**	65.5 ± 7.7	<0.001
GM rFa/LLL (%)	11.5 ± 1.7**	14.4 ± 1.5	<0.001
GM thickness (mm)	15.0 ± 2.2**	21.3 ± 3.1	<0.001
GM thickness/BW$^{0.33}$	4.0 ± 0.5**	4.9 ± 0.7	<0.001
GM rPa (°)	19.6 ± 2.7	20.1 ± 3.9	0.673
VL rFa (mm)	79.3 ± 8.2**	100.7 ± 17.7	<0.001
VL rFa/ULL (%)	19.2 ± 2.0*	23.7 ± 4.7	0.002
VL thickness (mm)	21.2 ± 2.4**	27.6 ± 3.0	<0.001
VL thickness/BW$^{0.33}$	5.6 ± 0.6*	6.4 ± 0.5	0.003
VL rPa (°)	15.3 ± 1.9	15.4 ± 1.6	0.914

*,** Statistically significant difference between groups (P ≤ 0.05 and P ≤ 0.001, respectively).

Table 3. Tendon morphology: *Free AT length, AT aponeurosis (apo) length, AT length and calculated AT moment arm for the Maasai and Caucasian group. Values are means ± SD and relative to body height (%).*

Variable	**Maasai (n=20)**	**Caucasian (n=8)**	**P-value**
Free AT length (cm)	5.5 ± 1.4*	6.9 ± 1.9	0.035
Free AT length/h (%)	3.2 ± 0.8	3.8 ± 1.1	0.129
AT apo length (cm)	17.7 ± 3.2*	14.9 ± 2.8	0.042
AT apo length/h (%)	10.4 ± 1.9*	8.1 ± 1.4	0.005
AT length (cm)	23.2 ± 3.1	21.9 ± 1.9	0.258
AT length/h (%)	13.6 ± 1.7*	11.9 ± 0.9	0.014
AT moment arm (cm)	4.7 ± 3.3	4.8 ± 1.8	0.773
AT moment arm/h (%)	2.8 ± 0.2*	2.6 ± 0.2	0.017

* Statistically significant difference between groups ($P \leq 0.05$).

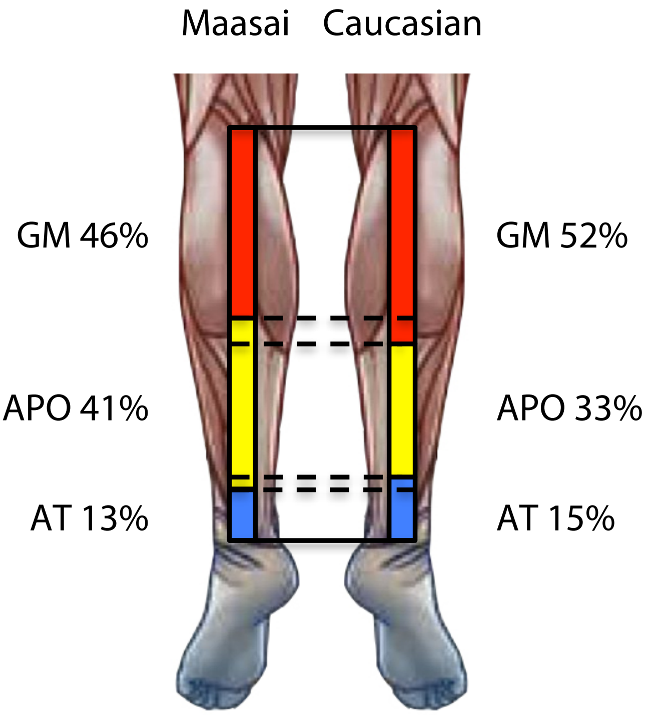


Figure 4. Tendon and muscle composition: *Relative length for the AT, the aponeurosis (APO) and the GM for the Maasai and the Caucasian control group. (Modified from Aftenposten A-magasinet, 29.07.16, p. 42.)*

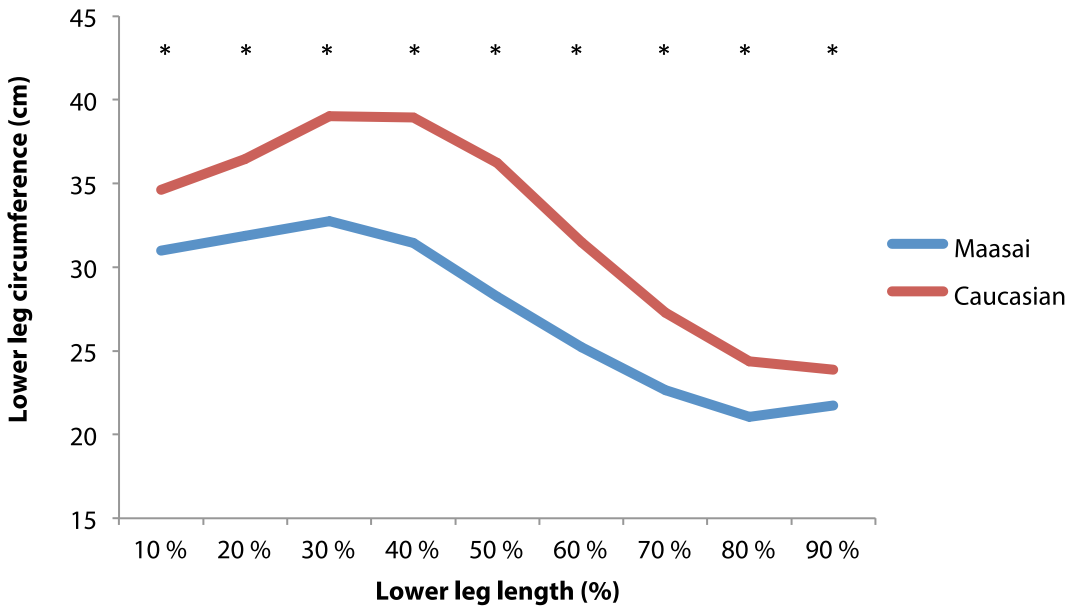


Figure 5. Lower leg circumference: *Lower leg circumference (cm) of the Maasai and Caucasian group measured at 10% intervals between the lateral epicondyle of femur (0%) and the lateral malleolus (100%). Averaged data for each group. * Statistically significant difference between groups (P < 0.001).*

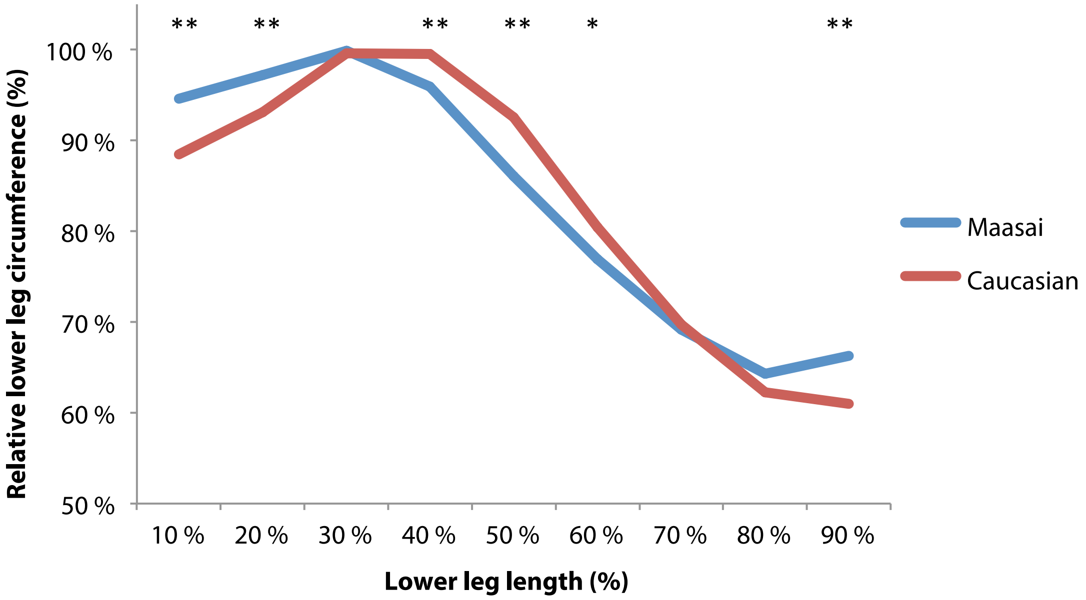


Figure 6. Relative lower leg circumference: *Relative lower leg circumference (%) of the Maasai and Caucasian group measured at 10% intervals between the lateral epicondyle of femur (0%) and the lateral malleolus (100%). 100% at the y-axis equals the highest of the nine measurements for each subject. Averaged data for each group. * ** Statistically significant difference between groups (P < 0.05 and P < 0.001, respectively).*

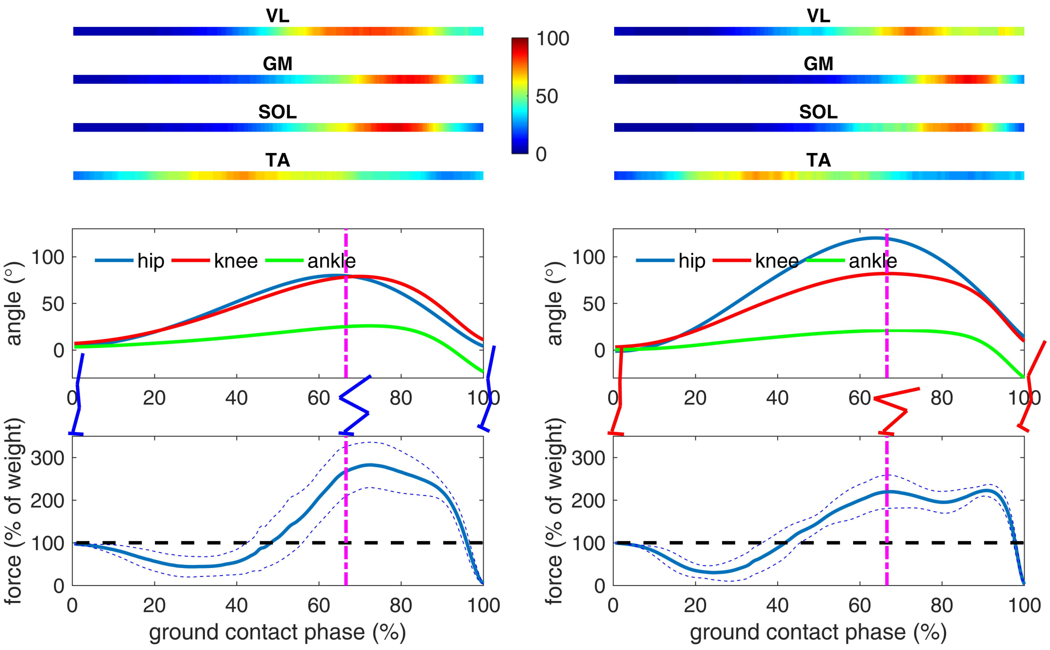


Figure 7. CMJ-data (%): *EMG-activation (%), joint angles (°) and ground reaction force (% to BW) for the Maasai (left) and the Caucasian (right) group during ground contact phase (%) of the CMJ. EMG-activation is ranging from blue (0%) to red (100%) based on peak values during maximal jumps. Joint angles (°) are relative to normal upright standing position. Force is reported relative to BW, including SD. The purple line indicates start of the concentric phase. Averaged data for each group.*

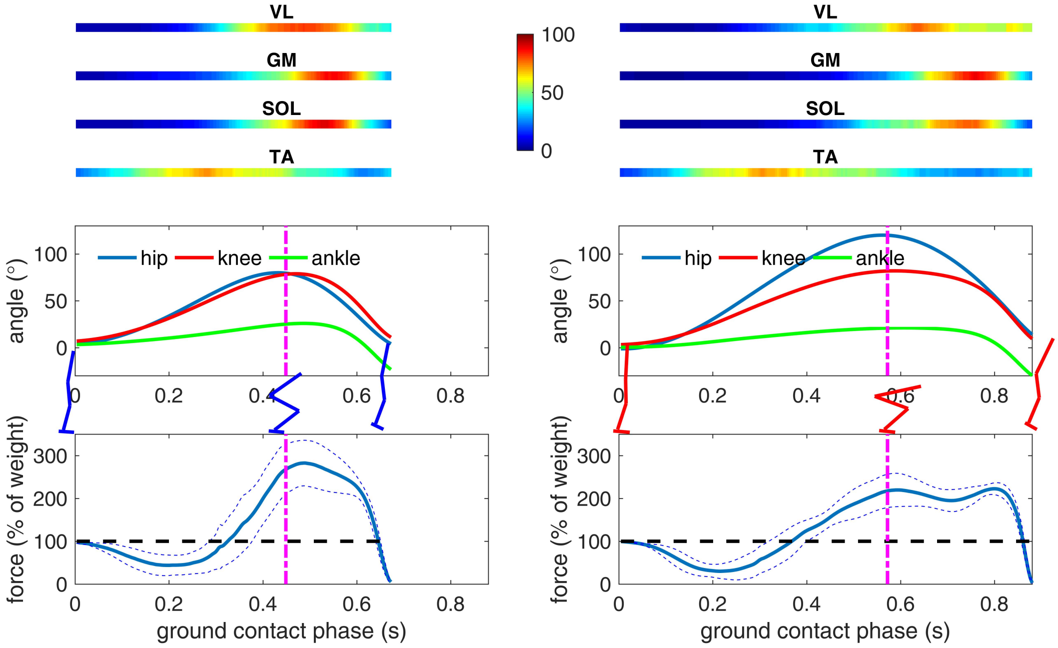


Figure 8. CMJ-data (s): *EMG-activation (%), joint angles (°) and ground reaction force (% to BW) for the Maasai (left) and the Caucasian (right) group during ground contact phase (s) of the CMJ. EMG-activation is ranging from blue (0%) to red (100%) based on peak values during maximal jumps. Joint angles (°) are relative to normal uright standing position. Force is reported relative to BW, including SD. The purple line indicates start of the concentric phase. Averaged data for each group.*

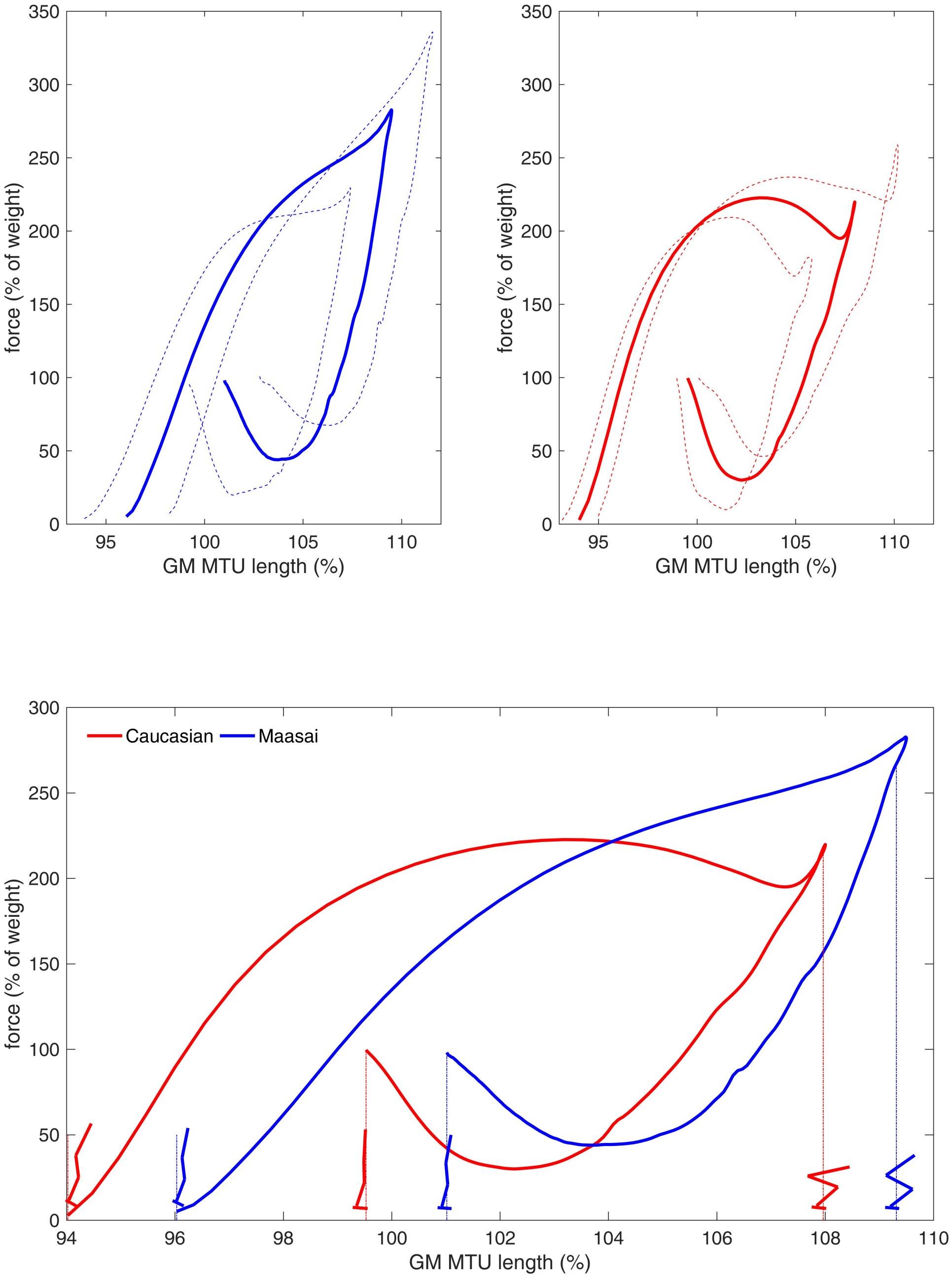


__Figure 9. MTU length of GM:__ Length of GM MTU (GM MTU length) in % relative to BW (%) during ground contact phase of the CMJ for the Maasai (blue) and Caucasian (red) group. Calculation is based on the formula by Hawkins & Hull (1990) and data is averaged for each group. The different starting position is due to different joint angles compared to upright standing position before initiating the jump.

Table 4. CMJ-variables: *Jump height (cm), net impulse (N/s), maximal power (W) and maximal force in the braking and push-off phases (N) in CMJ for the Maasai and Caucasian group. Values are means ± SD and stated in absolute values and relative to BW using allometric parameters (Unit).*

Variable	**Absolute values**		**P-value**	**Normalized to BW**		**Unit**	**P-value**
	Maasai (n=20)	**Caucasian (n=8)**		**Maasai (n=20)**	**Caucasian (n=8)**		
Jump height (cm)	33.3 ± 6.6*	40.0 ± 4.9	0.015	0.6 ± 0.1*	0.5 ± 0.1	P/BW^{0}	0.009
Net impulse (N/s)	142.6 ± 27.5**	237.3 ± 25.2	<0.001	9.6 ± 1.3**	12.1 ± 0.7	$P/BW^{0.67}$	<0.001
Max power (W)	2966.4 ± 748.4**	4678.7 ± 495.8	<0.001	198.8 ± 39.7*	238.7 ± 15.9	$P/BW^{0.67}$	0.011
Max force brake (N)	1559.2 ± 368.9	1814.0 ± 356.4	0.108	104.8 ± 20.2	92.5 ± 16.5	$P/BW^{0.67}$	0.140
Max force push (N)	1609.8 ± 371.9*	1987.0 ± 262.9	0.015	108.4 ± 20.8	101.3 ± 10.0	$P/BW^{0.67}$	0.370

*,** Statistically significant difference between groups ($P \leq 0.05$ and $P \leq 0.001$, respectively).

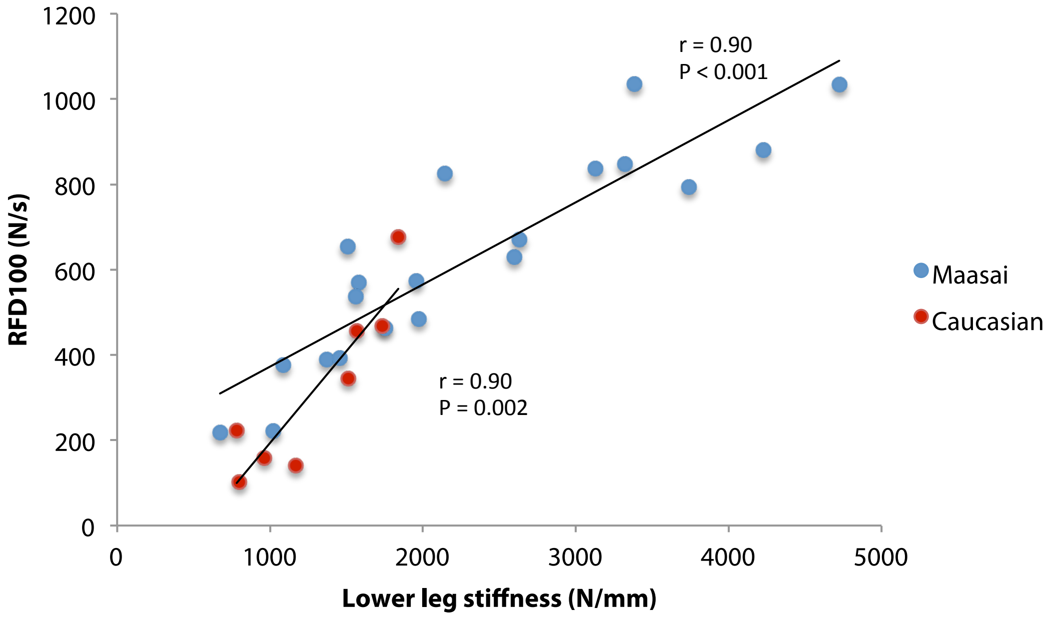


Figure 10. Lower leg stiffness vs RFD: *Lower leg stiffness (N/mm) was positively correlated to RFD at 100 ms (N/s) (RFD100) for both the Maasai ($r = 0.90$, $r^2 = 0.80$, $P < 0.001$) and Caucasian ($r = 0.90$, $r^2 = 0.81$, $P = 0.002$) group. Data is relative to BW using allometric parameters (RFD: $P/BW^{0.67}$, lower leg stiffness: $P/BW^{0.33}$).*

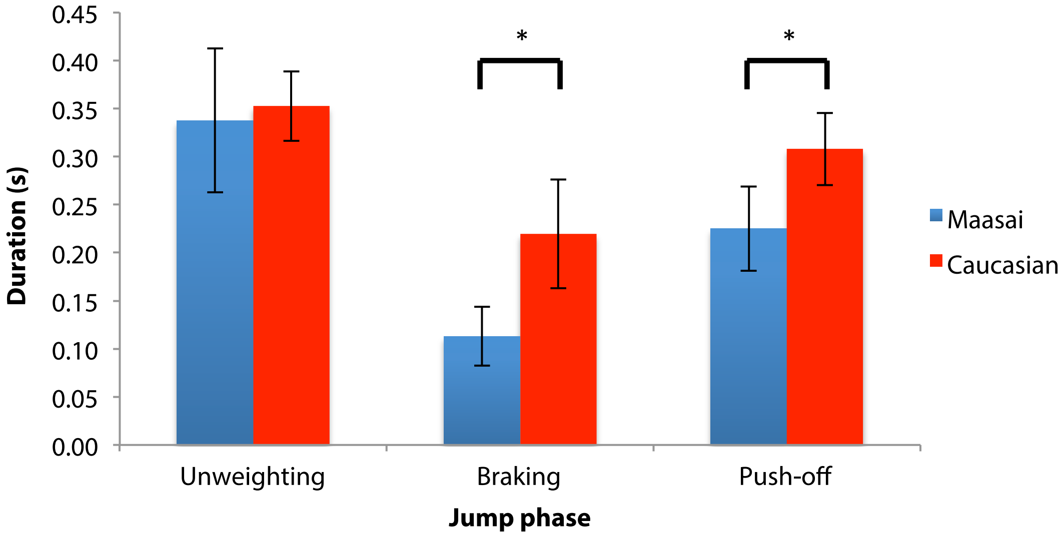


Figure 11. Jump phase duration: *Jump phase duration in seconds (s) for; unweighting phase, braking phase and push-off phase. * Statistically significant difference between groups (P < 0.001).*

Table 5. CMJ joint angles: *Ankle, knee and hip joint angles (°) in bottom position of the CMJ for the Maasai and Caucasian group. Bottom position equals the lowest point of center of mass. Angles are relative to normal upright standing position.*

Variable	**Maasai (n=20)**	**Caucasian (n=8)**	**P-value**
Ankle angle (°)	25.3 ± 5.1	20.9 ± 5.8	0.055
Knee angle (°)	79.0 ± 10.1	80.8 ± 13.2	0.544
Hip angle (°)	80.3 ± 12.8*	121.4 ± 10.0	<0.001

* Statistically significant difference between groups (P ≤ 0.001).

Table 6. Jump dance ritual variables: *Jump height (cm) and ankle, knee and hip joint angles (°) in the bottom position of the 'jump dance ritual' for the Maasai group. Bottom position equals the lowest point of each jump as evaluated by video analysis. Angles are relative to normal upright standing position.*

Variable	**Maasai (n=18)**
Jump height (cm)	46 ± 8.2
Ankle angle (°)	31 ± 2.6
Knee angle (°)	77 ± 6.1
Hip angle (°)	79 ± 10.1

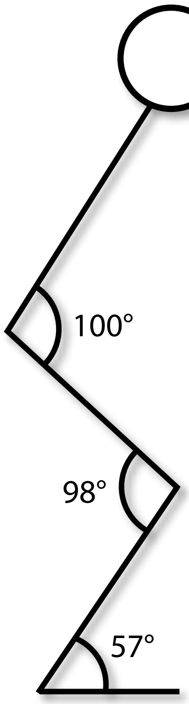


Figure 12. Jump dance ritual joint angles: *Basic model of ankle, knee and hip joint angles (°) in bottom position of the 'jump dance ritual' for the Maasai group. Bottom position equals the lowest point of each jump visual at the recorded video. Values are absolute.*

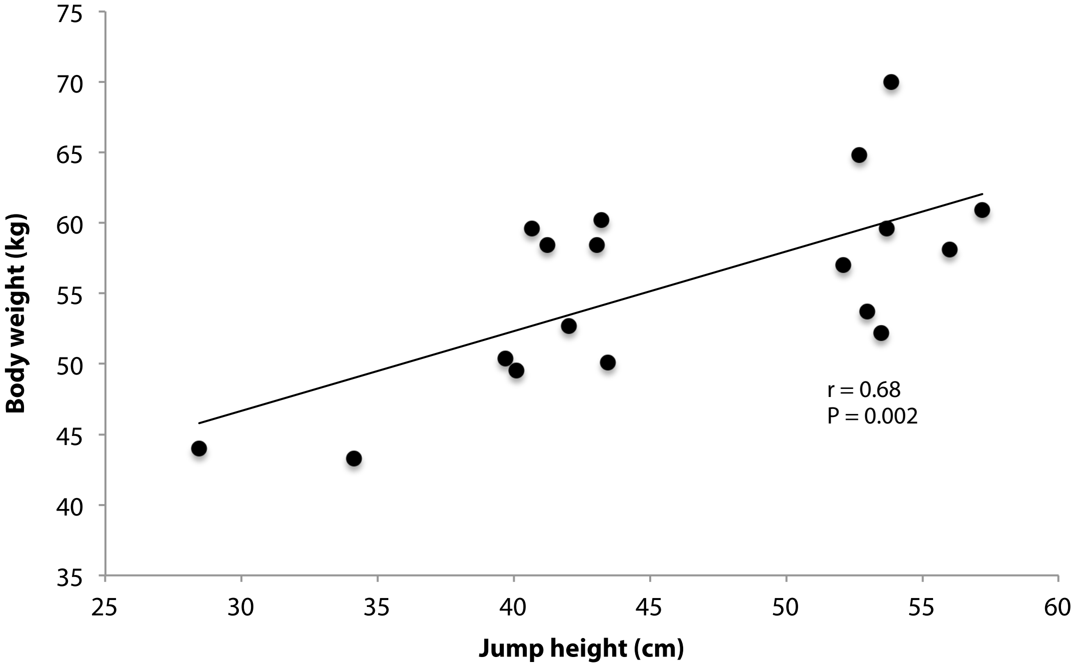


Figure 13. Jump dance ritual jump height vs BW (Maasai): *Jump height (cm) in the 'jump dance ritual' were positively related to BW (kg) for 18 Maasai subjects (r = 0.68,* $r^2 = 0.46$*, P = 0.002).*

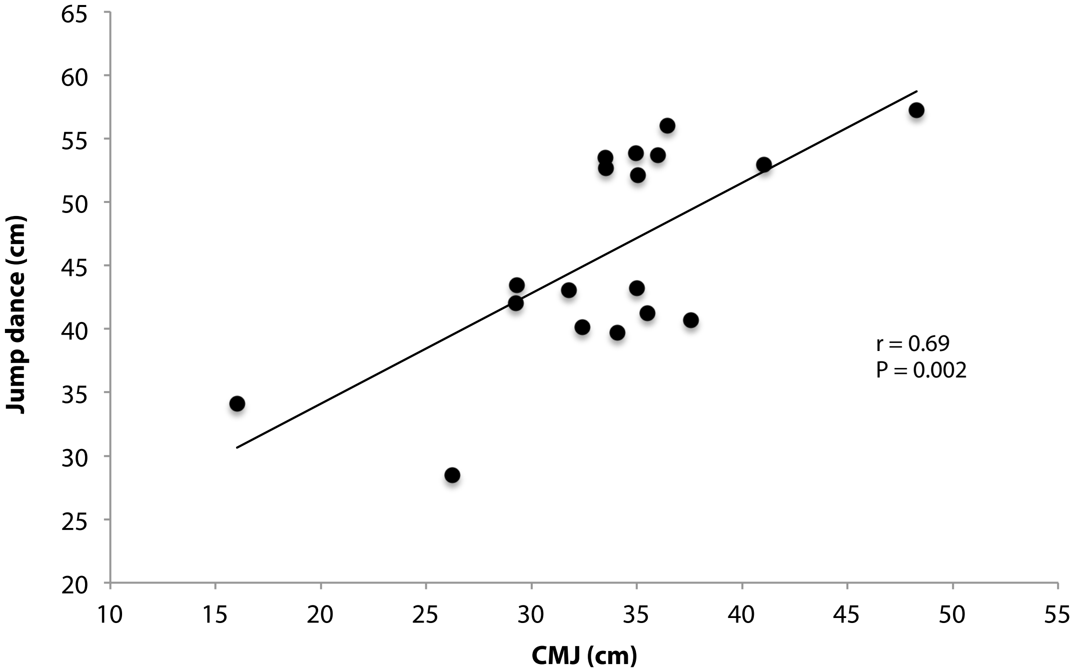


Figure 14. CMJ vs jump dance ritual jump height (Maasai): *Jump height (cm) in CMJ were positively correlated to jump height in the 'jump dance ritual' (cm) for 18 Maasai subjects (r = 0.69,* r^2 *= 0.47, P = 0.002).*

DISCUSSION

The present study examines differences in anthropometrics and CMJ variables between Maasai subjects and Caucasian controls. A similar study has not previously been performed and the present data may contribute to improve the understanding of Maasai anthropometrics and jump performance and a potential relation between these. Furthermore, such data can add valuable understanding of maximal VJ performance in humans in general as well.

Main findings. It was hypothesized that the Maasai individuals displayed distinctive anthropometrical features (e.g. a longer AT moment arm and shorter fascicles) and a significant jump performance. Based on the findings in the present study, Maasai subjects have a better relative jumping ability than Caucasian controls, despite a shorter loading time (Table 4 & Figure 11). Although it remains somewhat unclear if the difference between groups is related to anthropometrics, jumping technique or training, it is most reasonable that the main contributor to the relatively superior jumping performance in the Maasai was a better power amplification via elastic energy, such as; more appropriate tendon properties (e.g. morphology, stiffness and hysteresis), a better muscle mechanical advantage (e.g. moment arm), and an optimized strategy of series elastic elements loading. Nonetheless, the study presents unique data to understand the impressive jumping performance in Maasai individuals. Moreover, fascicle length and muscle thickness were less in GM and VL for the Maasai group both in absolute and relative values (Table 2). In addition, Maasai subjects had a longer AT, AT aponeurosis and AT moment arm relative to body height compared to the Caucasian controls (Table 3).

Anthropometrics. When adjusting for body height the Maasai subjects had a greater foot and hallux length compared to the controls (Table 1). Measured foot length is in line with findings by Choi et al. (2014) for Maasai of the same age, height and BW. Hallux length is previously shown to be significantly greater in sprinters compared to non-sprinters (Baxter & Piazza, 2014; Lee & Piazza, 2009), but whether this anatomical feature relates to jumping is not known. Maasai subjects also had a longer AT moment arm relative to body height compared to the Caucasian controls (Table 3) and might benefit from this due to a better muscle mechanical advantage (Lee & Piazza, 2009;

Scholz et al., 2008), although, it is shown that short moment arms could lead to increased storage of elastic energy in the AT and thus reduce the metabolic energy consumption (Scholz et al., 2008). Previous findings have shown that sprinters have a shorter AT moment arm and a longer hallux than height-matched non-sprinters (Lee & Piazza, 2009). On the contrary, another study investigating elite sprinters and slower sprinters reported no significant differences between groups in the length of the AT moment arm or the hallux (Karamanidis et al,. 2011). This is furthermore supported by an earlier study, which did not find any differences in AT moment arm from magnetic resonance imaging between runners and non-runners (Rosager et al., 2002).

There was no significant difference between groups in ULL and WLL (both in absolute or relative values), although ULL had a tendency to be greater in the Maasai in relative values. Lower leg length was longer for the controls in absolute values (certainly due to body height), but relative to body height there was no difference between groups (Table 1). Based on previous findings, lower leg length is shown to be positively correlated to CMJ height with arm swing in elite male volleyball players (Aouadi et al., 2012). Body height, BW and BMI were close to recent findings on age-matched Maasai individuals (Choi et al., 2014; Christensen et al., 2012). The significantly lower BMI in the Maasai group compared to the controls might be a factor that contributed to the higher jump height relative to BW, as BMI relates to a lower body fat percentage (Khosla & Lowe, 1967) which furthermore is shown to correlate with an increased jumping performance (Caia et al., 2016; Davis, Briscoe, Markowski, Saville, & Taylor, 2003).

Fascicle length and muscle thickness were less in Maasai subjects compared to the controls in both absolute and relative values in GM and VL (Table 2), but the present Maasai data were in line with previous findings with anthropometrically matched Kenyan runners for the GM (Sano et al., 2015). Short fascicles and low muscle thickness in the GM are contrary to what can be seen in e.g. sprinters (Abe et al., 2000; Kumagai et al., 2000). Due to these findings, it is unlikely that the greater jumping performance in the Maasai is a result of higher muscle force. It might on the other hand be related to fiber type composition (e.g. black sprinters usually have a higher amount of fast twitch fibres than whites (Ama et al., 1986)) and/or firing frequency (increased velocity), but this is only an assumption as the present study did not measure these parameters. Pennation angles were not significantly different in GM or VL between groups (Table 2), but close to what seen previous in the GM for untrained (Abe et al., 2000) and physically active male controls (Sano et al., 2013), and in the VL for moderately experienced power trained subjects (Methenitis et al., 2016).

AT length was longer in Maasai subjects (Table 3 & Figure 4), corresponding to preceding studies (Sano et al., 2013). Furthermore, the AT length of the controls in the present study corresponds to previous findings on trained male recreational distance runners (Hunter et al., 2015), accentuating the fact that the Maasai possess unique anthropometrical features. Moreover, the AT aponeurosis were longer for the Maasai, but free AT length did not differ between groups relative to body height (Table 3 & Figure 4). Given the smaller range of motion of the Maasai during the CMJ, one would assume that the tendon is less stretched. Since it is already longer, this mens that it would store less energy than the short tendon of the Caucasians which is more stretched. So, one explanation is that the AT has different material properties, making the Maasai tendon stiffer and able to store more energy despite the situation.

All lower leg circumference measurements were significantly lower in the Maasai subjects compared to the control group, close to previous findings for calf circumference on Maasai individuals (Choi et al., 2014), but slightly greater than anthropometrically matched Eritrean sprinters (Lucia et al., 2006). For the controls, the circumference was close to what is previously reported in elite sprinters (Vucetic, Matkovic, & Sentija, 2008). It also seemed like the Maasai subjects had shorter and differently shaped (distributed closer to the hip joint) muscles than the Caucasians, and a tendency to larger ankles (Figure 5 & 6).

Jump variables. EMG-signals were wider for the Maasai group compared to the controls, both in absolute and relative values (Figure 7 & 8). A possible interpretation would be that the Maasai have a different activation strategy which may relate to them being unfamiliar with the CMJ. Alternatively, it could be a result of trying to optimize the higher stiffness to the jump movement. Muscle activation timing seems similar for both groups, but shows a tendency of an earlier VL activation in the Caucasians, which could be a result of a more 'hip-dominant' push-off phase. The entire jump duration, and the braking and push-off phases, were considerably shorter for the Maasai group (Figure 8 & 11), which in addition lead to a faster rise in force. Hip flexion was significantly greater in the control group (Figure 7, 8 & Table 5). Previous investigations have demonstrated a lower maximal jump height (10%) when keeping the trunk as upright as possible (lower hip flexion) throughout the jump compared to when jumping with preferred hip flexion. Furthermore, the same study found that hip joint power decreased while knee joint power increased, which indicate that maximal jump performance does not necessarily represent maximal power of each individual joint (Vanrenterghem, Lees, & Clercq, 2008).

McBride & Snyder (2012) indicated that trained jumpers jumped higher and had greater mechanical efficiency, possibly as a result of great force production in the eccentric phase as a reflection of optimal MTU length change (and increased usage of elastic energy). In the present study a more or less equal change in GM MTU length was seen for both groups during the CMJ (Figure 9). Considering the present data are based on kinematics and standard values of moment arms (Hawkins & Hull, 1990), more detailed investigations are warranted to exactly determine the *in vivo* mechanics of the MTU during VJ. Maasai subjects produced a higher maximal force relative to BW compared to the Caucasians, but additionally lost it faster (Figure 9). This could probably be related to the shorter jump duration. In addition, a distinct difference in jumping strategy is clear. The force increase was more linear for the Maasai and did not have the somewhat double-peaked force curve as the controls. This might be related to increased plantar flexor work or a greater contribution from the trunk prior to take-off in the controls (Jakobsen et al., 2012).

CMJ height was lower in absolute values, but higher relative to BW in the Maasai subjects (Table 4). In relation to previous findings, the Maasai group achieved a higher relative jump height compared to subjects consisting of untrained controls (Jakobsen et al., 2012), volleyball players and cyclists (Bojsen-Moller et al., 2005; Hunter & Marshall, 2002). Net impulse were less in Maasai subjects due to shorter jump duration. Furthermore, max power was higher for the controls both in relative and absolute values (Table 4). For the Maasai, the relative (to BW) values were in line with preceding investigations (Bojsen-Moller et al., 2005). As power is related to angular velocities, it is likely that Caucasians have faster angular speeds (Levangie & Norkin, 2011). No significant differences between groups in maximal force for the push-off and braking phases relative to BW were found.

Lower leg stiffness was positively correlated to RFD at 100 ms relative to BW for both the Maasai and Caucasian group (Figure 10) in accordance with previous findings (Bojsen-Moller et al., 2005), although the RFD from the present study was determined based on rise in force during jumping (lower leg stiffness), whereas that of Bojsen-Moller et al. (2005) included isometric measurements of RFD. Additionaly, the stiffness in the Bojsen-Moller et al. (2005) study was based on tendon stiffness measured with US, which might lower the relationship. Neural aspects and/or firing frequency may have played a role in the results, but due to methodological limitations these factors were not examined in the present study. RFD was in the present study calculated as the average tangential slope at 0-100 ms relative to the start of the eccentric deceleration phase (Thorlund et al., 2008). Although the intra-group relation was high, the inter-group relation was highly different. These findings are assumably due to different jump strategies with different effectiveness. A feasible explanation could be that the limited range of motion while jumping in the Maasai leads to higher leg stiffness. This is supported by previous investigations that indicate that increased CMJ depth reduced leg stiffness (Hunter & Marshall, 2002). Furthermore, Fukashiro, Abe, Shibayama, & Brechue (2002) found a higher stiffness in black sprint type athletes than in white comparable athletes, although this study estimated muscle stiffness.

The 'jump dance ritual' consisted of repetitive, but rather maximal jumps. The Maasai did not get any other instructions prior to these jumps than to do to their traditional 'jump dance ritual'. Average jump height was 46 cm (Table 6), a remarkable difference from the CMJ, but moreover in line with what preliminary observations by Dirk Lund Christensen (personal coummunication) suggested and close to maximal CMJ with arms akimbo in male volleyball players (de Ruiter et al., 2007; Gheller et al., 2015). Since joint angles in the 'jump dance ritual' and CMJ were almost identical (Table 5 & 6), Maasai subjects most likely benefit from a changed motor strategy during this task. The results demonstrate that the CMJ has limited feasibility for assessing jump height in Maasasi and that a lot more substantial familiarization is necessary (that was simply not feasible in the present study).

Correlation between BW and jump height in the 'jump dance ritual' were moderately positive (Figure 13), which corresponds to recent findings investigating VJ performance (Caia et al., 2016). Even though the CMJ task was challenging for the Maasai subjects, these jumps had a moderate positive correlation to the ‘jump dance ritual’ jump height (Figure 14). These findings demonstrate that even though the Maasai are limited in the CMJ movement, it still reflects somehow the ability to perform VJ. It is important not to forget that BW may play an important role for this result (Caia et al., 2016).

During the ‘jump dance ritual ceremony’, the Maasai subjects positioned themselves in a half-circle. One at a time a Maasai took a step forward and made approximately 3-10 jumps, usually ending with the highest jump. After completing the jumps, the Maasai went back into the half-circle continuing chanting with the other jumpers. An interesting observation was that the Maasai made a horizontal nodding movement while jumping. In addition, the end of each jump series was consistently finished with a forceful landing, which actually seemed like a rivalry in itself. This was also the fact when performing CMJ. Furthermore, a valgus knee movement during each ground contact phase was observed in the Maasai, but due to analysis limitations (two-dimensional only) this was not possible to quantify.

Limitations. The most pronounced limitation of the study is the fact that the groups could not be matched for height and BW. In addition, due to time constraints for the present thesis the control group was smaller and consisting of both active controls and jumping athletes. A more equal control group would have eliminated the need for normalization. There were initially 20 participating Maasai subjects in the study. All Maasai subjects completed the maximal jump tests, but only 18 Maasai were able to perform the ‘jump dance ritual’.

It was clear that the Maasai subjects were not used to the CMJ task, thinking it was unnatural and technically challenging. Lack of maximal EMG-amplitude during e.g. MVC contractions, meant that the only potential muscle activation factor to examine was timing. It is usually agreed that the knee angle when performing a CMJ should be somewhat around 90 degrees (Cavagna, Dusman, & Margaria, 1968; Thorlund et al., 2008). Despite this we agreed that every subject could choose their preferred knee-angle, because the Maasai subjects had difficulty performing the CMJ technique (Bojsen-Moller et al., 2005). Even though the subjects performed several jumps, only the single highest jump was used for the CMJ analysis. Only Maasai subjects completed the ‘jump dance ritual’ testing, hence no intergroup comparison was conducted.

Furthermore, no maximal reference EMG was measured, which limits the interpretation of EMG activation. For some jumps, EMG-data had to be eliminated due to non-physiological artifacts. The custom-built force plate was lightweight and was able to undergo displacement of < 5 mm despite thorough fixation to the floor of the lab. Although procedures were adopted to ensure instant repositioning of the force plate in case of displacement, it is plausible that this movement could have influenced the data to a small degree. Using a force sampling frequency of more than 300 Hz might contribute to reduce the potential measurement error of 2% (Street et al., 2001). In addition, analysis of the 'jump dance ritual' variables were done manually and could have been more accurate e.g. using calculation based on ground reaction forces, several reflective markers and a custom tracking software. Moreover, conclusions should be drawn with care considering the limitations and the fact that this study is the first of its kind on Maasai subjects.

Conclusion. The present study has shown that Maasai subjects achieve higher CMJ than Caucasian controls when adjusting for BW. The Maasai also practice a more upright jumping strategy than the controls. Time duration of the braking and push-off phases were shorter for Maasai subjects. Fascicle length and muscle thickness were less in GM and VL for the Maasai group both in absolute and relative values. Maasai subjects had a longer AT, AT aponeurosis and AT moment arm relative to body height compared to the controls. Additionally, 'jump dance ritual' jump height in the Maasai was remarkable and close to 50 cm. The present study is the first to incorporate precise biomechanical methodology to investigate jumping performance in Maasai individuals. The study demonstrates clear differences in anthropometry between groups and combined with the Maasai lifestyle (consisting of traditional jumping rituals and a high volume of daily activity) the study sheds light on the factors that underlie the impressive jumping capabilities in Maasai individuals. The Maasai possess significant jumping performance despite no specific strength or plyometric training history as common in western world jumping athletes. Conclusively, muscle thickness and fascicle length measurements strengthen the fact that the superior relative jumping performance in the Maasai not was a result of higher muscle force. Albeit, it is more likely that the main contributor was a better power amplification via elastic energy, such as; more appropriate tendon properties (e.g. morphology, stiffness and hysteresis), a better muscle mechanical advantage (e.g. moment arm), and an optimized strategy of series elastic elements loading (rate of loading, connected to movement strategy and limb stiffness).

Perspectives. To further improve the understanding of the impressive jumping performance in Maasai individuals, future perspectives would be to recruit a more appropriate control group for a more homogenous match of body height and BW. In addition, the size of the control group should be larger (somewhat equivalent to the Maasai group). Another interesting factor would be to split the control group into two individual groups, including one sedentary group and one group consisting of jumping athletes, and thus compare data between three different groups (sedentary controls, trained jumping athletes and Maasai individuals). Inclusion of a drop jump test (to possibly involve other physiological and musculoskeletal qualities) (Arampatzis, Schade, Walsh, & Bruggemann, 2001), a fiber type investigation (biopsy) and a more extensive analysis of the Maasai 'jump dance ritual' would be favorable as well.

References

Abe, T., Kumagai, K., & Brechue, W. F. (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Med Sci Sports Exerc, 32*(6), 1125-1129.

Ama, P. F., Simoneau, J. A., Boulay, M. R., Serresse, O., Theriault, G., & Bouchard, C. (1986). Skeletal muscle characteristics in sedentary black and Caucasian males. J Appl Physiol (1985), 61(5), 1758-1761.

Aouadi, R., Jlid, M. C., Khalifa, R., Hermassi, S., Chelly, M. S., Van Den Tillaar, R., & Gabbett, T. (2012). Association of anthropometric qualities with vertical jump performance in elite male volleyball players. J Sports Med Phys Fitness, 52(1), 11-17.

Arampatzis, A., Schade, F., Walsh, M., & Bruggemann, G. P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. J Electromyogr Kinesiol, 11(5), 355-364.

Baxter, J. R., & Piazza, S. J. (2014). Plantar flexor moment arm and muscle volume predict torque-generating capacity in young men. J Appl Physiol (1985), 116(5), 538-544. doi:10.1152/japplphysiol.01140.2013

Benard, M. R., Becher, J. G., Harlaar, J., Huijing, P. A., & Jaspers, R. T. (2009). Anatomical information is needed in ultrasound imaging of muscle to avoid potentially substantial errors in measurement of muscle geometry. *Muscle Nerve, 39*(5), 652-665. doi:10.1002/mus.21287

Bojsen-Moller, J., Magnusson, S. P., Rasmussen, L. R., Kjaer, M., & Aagaard, P. (2005). Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *J Appl Physiol (1985), 99*(3), 986-994. doi:10.1152/japplphysiol.01305.2004

Caia, J., Weiss, L. W., Chiu, L. Z., Schilling, B. K., Paquette, M. R., & Relyea, G. E. (2016). Do Lower-Body Dimensions and Body Composition Explain Vertical Jump Ability? *J Strength Cond Res, 30*(11), 3073-3083. doi:10.1519/JSC.0000000000001406

Cavagna, G. A., Dusman, B., & Margaria, R. (1968). Positive work done by a previously stretched muscle. *J Appl Physiol, 24*(1), 21-32.

Choi, J. Y., Suh, J. S., & Seo, L. (2014). Salient features of the Maasai foot: analysis of 1,096 Maasai subjects. *Clin Orthop Surg, 6*(4), 410-419. doi:10.4055/cios.2014.6.4.410

Christensen, D. L., Faurholt-Jepsen, D., Boit, M. K., Mwaniki, D. L., Kilonzo, B., Tetens, I., . . . Brage, S. (2012). Cardiorespiratory fitness and physical activity in Luo, Kamba, and Maasai of rural Kenya. *Am J Hum Biol, 24*(6), 723-729. doi:10.1002/ajhb.22303

Davis, D. S., Briscoe, D. A., Markowski, C. T., Saville, S. E., & Taylor, C. J. (2003). Physical characteristics that predict vertical jump performance in recreational male athletes. *Physical Therapy in Sport, 4*, 167-174.

De Luca, C. J. (1997). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics, 13*, 135-163.

de Ruiter, C. J., Vermeulen, G., Toussaint, H. M., & de Haan, A. (2007). Isometric knee-extensor torque development and jump height in volleyball players. *Med Sci Sports Exerc, 39*(8), 1336-1346. doi:10.1097/mss.0b013e318063c719

Fauth, M. L., Petushek, E. J., Feldmann, C. R., Hsu, B. E., Garceau, L. R., Lutsch, B. N., & Ebben, W. P. (2010). Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting. *J Strength Cond Res, 24*(4), 1131-1137. doi:10.1519/JSC.0b013e3181cc2353

Fukashiro, S., Abe, T., Shibayama, A., & Brechue, W. F. (2002). Comparison of viscoelastic characteristics in triceps surae between Black and White athletes. Acta Physiol Scand, 175(3), 183-187. doi:10.1046/j.1365-201X.2002.00985.x

Gheller, R. G., Dal Pupo, J., Ache-Dias, J., Detanico, D., Padulo, J., & dos Santos, S. G. (2015). Effect of different knee starting angles on intersegmental coordination and performance in vertical jumps. Hum Mov Sci, 42, 71-80. doi:10.1016/j.humov.2015.04.010

Hawkins, D., & Hull, M. L. (1990). A method for determining lower extremity muscle-tendon lengths during flexion/extension movements. *J Biomech, 23*(5), 487-494.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol, 10*(5), 361-374.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc, 41*(1), 3-13. doi:10.1249/MSS.0b013e31818cb278

Hunter, G. R., McCarthy, J. P., Carter, S. J., Bamman, M. M., Gaddy, E. S., Fisher, G., . . . Newcomer, B. R. (2015). Muscle fiber type, Achilles tendon length, potentiation, and running economy. J Strength Cond Res, 29(5), 1302-1309. doi:10.1519/JSC.0000000000000760

Hunter, J. P., & Marshall, R. N. (2002). Effects of power and flexibility training on vertical jump technique. *Med Sci Sports Exerc, 34*(3), 478-486.

Ishikawa, M., & Komi, P. V. (2007). The role of the stretch reflex in the gastrocnemius muscle during human locomotion at various speeds. *J Appl Physiol (1985), 103*(3), 1030-1036. doi:10.1152/japplphysiol.00277.2007

Jakobsen, M. D., Sundstrup, E., Randers, M. B., Kjaer, M., Andersen, L. L., Krustrup, P., & Aagaard, P. (2012). The effect of strength training, recreational soccer and running exercise on stretch-shortening cycle muscle performance during countermovement jumping. Hum Mov Sci, 31(4), 970-986. doi:10.1016/j.humov.2011.10.001

Jaric, S. (2003). Role of body size in the relation between muscle strength and movement performance. *Exerc Sport Sci Rev, 31*(1), 8-12.

Karamanidis, K., Albracht, K., Braunstein, B., Moreno Catala, M., Goldmann, J. P., & Bruggemann, G. P. (2011). Lower leg musculoskeletal geometry and sprint performance. Gait Posture, 34(1), 138-141. doi:10.1016/j.gaitpost.2011.03.009

Khosla, T., & Lowe, C. R. (1967). Indices of obesity derived from body weight and height. *Br J Prev Soc Med, 21*(3), 122-128.

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. J Appl Physiol (1985), 88(3), 811-816.

Kwah, L. K., Pinto, R. Z., Diong, J., & Herbert, R. D. (2013). Reliability and validity of ultrasound measurements of muscle fascicle length and pennation in humans: a systematic review. *J Appl Physiol (1985), 114*(6), 761-769. doi:10.1152/japplphysiol.01430.2011

Lee, S. S., & Piazza, S. J. (2009). Built for speed: musculoskeletal structure and sprinting ability. J Exp Biol, 212(Pt 22), 3700-3707. doi:10.1242/jeb.031096

Levangie, P. K., & Norkin, C. C. (2011). Joint Structure and Function: A Comprehensive Analysis. Fifth Edition: F.A. Davis.

Lucia, A., Esteve-Lanao, J., Olivan, J., Gomez-Gallego, F., San Juan, A. F., Santiago, C., . . . Foster, C. (2006). Physiological characteristics of the best Eritrean runners-exceptional running economy. Appl Physiol Nutr Metab, 31(5), 530-540. doi:10.1139/h06-029

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *J Strength Cond Res, 18*(3), 551-555. doi:10.1519/1533-4287(2004)18<551:RAFVOS>2.0.CO;2

Markovic, G., & Jaric, S. (2004). Movement performance and body size: the relationship for different groups of tests. *Eur J Appl Physiol, 92*(1-2), 139-149. doi:10.1007/s00421-004-1076-7

McBride, J. M., & Snyder, J. G. (2012). Mechanical efficiency and force-time curve variation during repetitive jumping in trained and untrained jumpers. Eur J Appl Physiol, 112(10), 3469-3477. doi:10.1007/s00421-012-2327-7

Methenitis, S. K., Zaras, N. D., Spengos, K. M., Stasinaki, A. N., Karampatsos, G. P., Georgiadis, G. V., & Terzis, G. D. (2016). Role of Muscle Morphology in Jumping, Sprinting, and Throwing Performance in Participants With Different Power Training Duration Experience. J Strength Cond Res, 30(3), 807-817. doi:10.1519/JSC.0000000000001147

Rosager, S., Aagaard, P., Dyhre-Poulsen, P., Neergaard, K., Kjaer, M., & Magnusson, S. P. (2002). Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. Scand J Med Sci Sports, 12(2), 90-98.

Sano, K., Ishikawa, M., Nobue, A., Danno, Y., Akiyama, M., Oda, T., . . . Komi, P. V. (2013). Muscle-tendon interaction and EMG profiles of world class endurance runners during hopping. *Eur J Appl Physiol, 113*(6), 1395-1403. doi:10.1007/s00421-012-2559-6

Sano, K., Nicol, C., Akiyama, M., Kunimasa, Y., Oda, T., Ito, A., . . . Ishikawa, M. (2015). Can measures of muscle-tendon interaction improve our understanding of the superiority of Kenyan endurance runners? *Eur J Appl Physiol, 115*(4), 849-859. doi:10.1007/s00421-014-3067-7

Scholz, M. N., Bobbert, M. F., van Soest, A. J., Clark, J. R., & van Heerden, J. (2008). Running biomechanics: shorter heels, better economy. *J Exp Biol, 211*(Pt 20), 3266-3271. doi:10.1242/jeb.018812

Seynnes, O. R., Maganaris, C. N., de Boer, M. D., di Prampero, P. E., & Narici, M. V. (2008). Early structural adaptations to unloading in the human calf muscles. *Acta Physiol (Oxf), 193*(3), 265-274. doi:10.1111/j.1748-1716.2008.01842.x

Sheppard, J. M., Cronin, J. B., Gabbett, T. J., McGuigan, M. R., Etxebarria, N., & Newton, R. U. (2008). Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *J Strength Cond Res, 22*(3), 758-765. doi:10.1519/JSC.0b013e31816a8440

Stafilidis, S., & Arampatzis, A. (2007). Muscle - tendon unit mechanical and morphological properties and sprint performance. *J Sports Sci, 25*(9), 1035-1046. doi:10.1080/02640410600951589

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining countermovement jump height with the impulse method. *Journal of Applied Biomechanics, 17*, 43-54.

Thorlund, J. B., Michalsik, L. B., Madsen, K., & Aagaard, P. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scand J Med Sci Sports, 18*(4), 462-472. doi:10.1111/j.1600-0838.2007.00710.x

Vanrenterghem, J., Lees, A., & Clercq, D. D. (2008). Effect of forward trunk inclination on joint power output in vertical jumping. J Strength Cond Res, 22(3), 708-714. doi:10.1519/JSC.0b013e3181636c6c

Vucetic, V., Matkovic, B. R., & Sentija, D. (2008). Morphological differences of elite Croatian track-and-field athletes. *Coll Antropol, 32*(3), 863-868.

Appendix 2: Full experimental protocol

Full experimental trial

Caucasian subjects met one time in the lab at the Norwegian School of Sport Sciences, Oslo, Norway. Maasai subjects met one time in the field lab in Monduli Juu, Monduli, Tanzania. Although all subjects started with anthropometric measurements, the order of the three other parts of the investigation was not the same in Norway and Tanzania. The controls started out with maximal jumps, followed by repetitive jumps and ultimately maximal isometric plantar flexions, while the Maasai subjects began with the maximal isometric plantar flexion, before completing maximal jumps and repetitive jumps.

Anthropometrics. Measures of height and BW was taken, and age was reported. As Maasai individuals often are unaware of their actual biological age, the reported age is only an approximation. Digital images was taken perpendicular of the foot standing upright on a measuring board before free AT length and AT aponeurosis length, along with resting muscle architecture and muscle thickness of GM and VL, were measured with an US-system (LogicScan 128 EXT-1Z, Telemed, Lithuania), with a linear 60 mm transducer (scanning frequency: 12 MHz, HL9.0/60/128Z-2, Telemed, Lithuania) from a prone position lying on a bench. Lower and upper leg length and distribution of lower leg mass was measured from an upright standing position using a measuring tape.

Maximal isometric plantar flexion. Maximal isometric plantar flexion was measured in a custom-built chair. The chair was fairly light and optimized for transport, but still rigid. As a control of ankle joint displacement, subjects tested in Norway wore a wired electric goniometer (Noraxon Inc., Scottsdale, AZ, USA) attached to their dorsum and anteroir on their lower leg. The amount of ankle joint displacement was no larger than expected from the displacement of mass on the foot during a maximal contraction. A wired load cell (Noraxon Inc., Scottsdale, AZ, USA) measured the force (N) applied to the footplate. Subjects were asked to gradually increase the force for approximately three seconds before reaching maximal force. As maximal force was achieved the subjects were told to decrease the force at the same controlled pace. All subjects performed 2-3 trials in order to achieve maximal force. As the Maasai were unfamiliar with the concept of MVC, a near maximal force with a gradual incline of force was accepted. Data was captured in a MATLAB-script (R2015a, The MathWorks, Inc, Kista, Sweden).

Maximal jumping. CMJ were performed from an upright standing position with arms akimbo throughout the jump to minimize any influence from the arms. The subjects kept their feet parallel at a distance equal to the width of their shoulders. Following a signal from the test-leader, the subjects made a rapid downward movement by flexing their hip, knees and ankles and then immediately jumped as high as possible. The subjects were generally instructed to jump as high and as fast as possible and otherwise use their preferred jumping technique. SJ was initiated from the same position as the CMJ. Subjects were instructed to slowly flex their knees, stop for a few seconds and then jump as high as possible while trying to avoid any countermovement. To ensure a somewhat similar starting position, all subjects were instructed to start the jump with a knee angle of approximately 90 degrees. Hip angle was self-determined. The outcome from this test was not successful or valid, as the Maasai had difficulty coordinating the movement, not able to eliminate a countermovement in the beginning of the jump, despite having up to five attempts. Due to this, no SJ data were included in the results. During the traditional Maasai ‘jump dance ritual’ testing, subjects (only Maasai) were instructed to jump as close to their normal ritual despite the somewhat awkward situatuon of being in the lab. Subjects were allowed to carry both their stick, knife and full clothing while jumping, and a group of Maasai were chanting and dancing close by to resemble the jumping ceremony.

Repetitive jumping. During the repetitive jumping trials the subjects were told to jump repeatedly at their own preferred pace, not to pull their feet to the air and keep their arms akimbo. Recording was started when a controlled pace and a good rhythm were established. After one recording the subjects got an approximately two minute break while saving data. After 2-3 successful submaximal trials subjects were told to jump maximally, but still repeatedly. During these jumps, keeping balance and staying inside of the force plate was more challenging, and subjects were therefore told to look at a point or an item to better control the landing of each jump. 2-3 successful maximal trials were captured. For both conditions subjects jumped for approximately 20 seconds during each trial, where ten seconds were recorded and another ten seconds was used for finding balance and a controlled even pace.

Appendix 3: Written informed consent form

Forespørsel om deltagelse i forsøksprosjekt

Dette er et spørsmål til deg om å delta i et forskningsstudie som omhandler hopp-prestasjon og muskel-sene-funksjon i underekstremiteten. Formålet er å sammenlikne Maasai-folket med nordiske atleter og kontroller. Prosjektet er et masterprosjekt ved Norges idrettshøgskole, og gjennomføres under veiledning av hovedveileder Jens Bojsen-Møller og biveileder Olivier Seynnes.

Bakgrunnen for studiet

Formålet med dette prosjektet er å sammenlikne hopp-prestasjon og muskel-sene funksjon i underekstremiteten til Maasai-folket med nordiske atleter og kontrollpersoner. Muskelaktivering, mekaniske egenskaper i sene og aponeurose, samt evnen til å lagre og frigjøre energi i kraftoverførende vev er alle viktige faktorer for hopp-prestasjon. Den direkte sammenhengen mellom disse faktorene er fremdeles uklart. Maasai-folket er et nomadefolk som lever i områder rundt grensen mellom Kenya og Tanzania. De praktiserer stammeritualer hvor det er observert ekstreme hopphøyder, > 50 cm. Det kan tenkes at deres livsstil, kultur og tradisjoner har bidratt til å oppnå ekstreme hopp-prestasjoner.

Hovedmål

(1) Undersøke hopp-prestasjon (maks hopphøyde og power i underekstremiteten) samt muskel-sene-funksjonen og biomekaniske egenskaper i de kraftbærende vevene i Maasai-folket.
(2) Sammenlikne disse dataene med tilsvarende data fra kontrollpersoner og erfarne atleter innen hoppidretter.

Hva inneholder studien?

Forsøkspersonene vil bli testet på laboratoriet for bevegelsesanalyse ved Norges idrettshøgskole. Testene som gjennomføres vil bestå av antropometriske målinger, senestivhet i akillessenen, samt maksimale og repetitive hopp.

Fordeler og ulemper

Deltakelsen i prosjektet krever noe tid og oppmerksomhet, da testingen tar i overkant av to timer. Vi vil tilpasse oppmøtet slik at det passer for forsøkspersonene.

Forsøkspersonene må selv ta seg til Norges idrettshøgskole, og vil ikke få dekket reisekostnader. Det ønskes at forsøkspersonene ikke gjennomfører tung beintrening dagen før eller på selve testdagen, da dette kan påvirke testresultatene. Det er svært liten risiko for skade under gjennomføring av disse testene, men det kan forekomme stølhet de påfølgende dagene. Deltagelsen vil gi deg et innblikk i hvordan tester og forskning rundt fysiske egenskaper utføres. Du kan som forsøksperson til enhver tid, før og under studiet, trekke deg uten å oppgi begrunnelse.

Hva skjer med dine testresultater og opplysninger?

Alle personlige opplysninger, samt testresultatene, vil være avidentifisert under forsøksperioden og anonymisert når studien er gjennomført. Dette betyr at du ved forsøksstart vil få utdelt et forsøkspersonnummer som skal brukes under studien. Det er kun dette nummeret som vil være direkte knyttet til dine data. Listen som viser hvilket forsøkspersonnummer du har vil bli slettet når studien er ferdig. Da vil det ikke være mulig knytte dine data til din person. Det vil derfor ikke være mulig å identifisere deg i resultatene fra studien når disse senere publiseres.

Samtykke til deltagelse i studien

Om du har lest informasjonsskrivet og ønsker deltagelse i prosjektet, kan du signere “samtykke om deltagelse” nedenfor. Dersom du ønsker å trekke deg eller har noen spørsmål, ta kontakt med en av oss:

- Andreas Skiri Refsdal, 476 27 373	andreasrefsdal@gmail.com
- Herman Hernæs, 416 04 232	herman.hernaes@gmail.com
- Jens Bojsen-Møller, 23 26 22 34	jens.bojsen-moller@nih.no
- Olivier Seynnes, 23 26 23 08	olivier.seynnes@nih.no

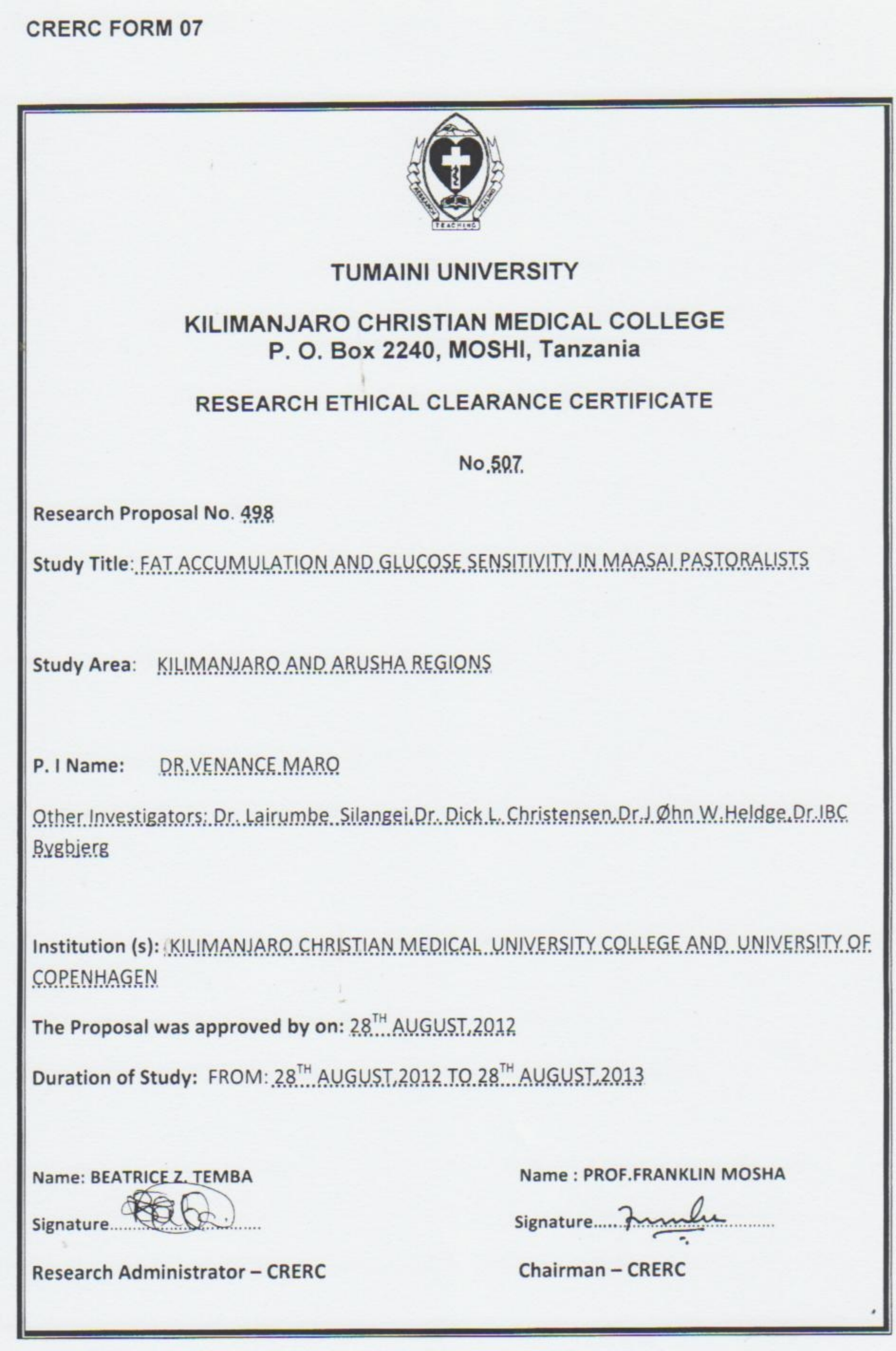
Jeg er villig til å delta i studien

(signert av prosjektdeltaker, dato)

Jeg bekrefter å ha gitt informasjon om studien

(signert av testansvarlig, dato)

Appendix 4: Ethics approval



CRERC FORM 07

TUMAINI UNIVERSITY

KILIMANJARO CHRISTIAN MEDICAL COLLEGE
P. O. Box 2240, MOSHI, Tanzania

RESEARCH ETHICAL CLEARANCE CERTIFICATE

No 507

Research Proposal No. 498

Study Title: FAT ACCUMULATION AND GLUCOSE SENSITIVITY IN MAASAI PASTORALISTS

Study Area: KILIMANJARO AND ARUSHA REGIONS

P. I Name: DR.VENANCE MARO

Other Investigators: Dr. Lairumbe Silangei,Dr. Dick L. Christensen,Dr.J Øhn W.Heldge,Dr.IBC Bygbjerg

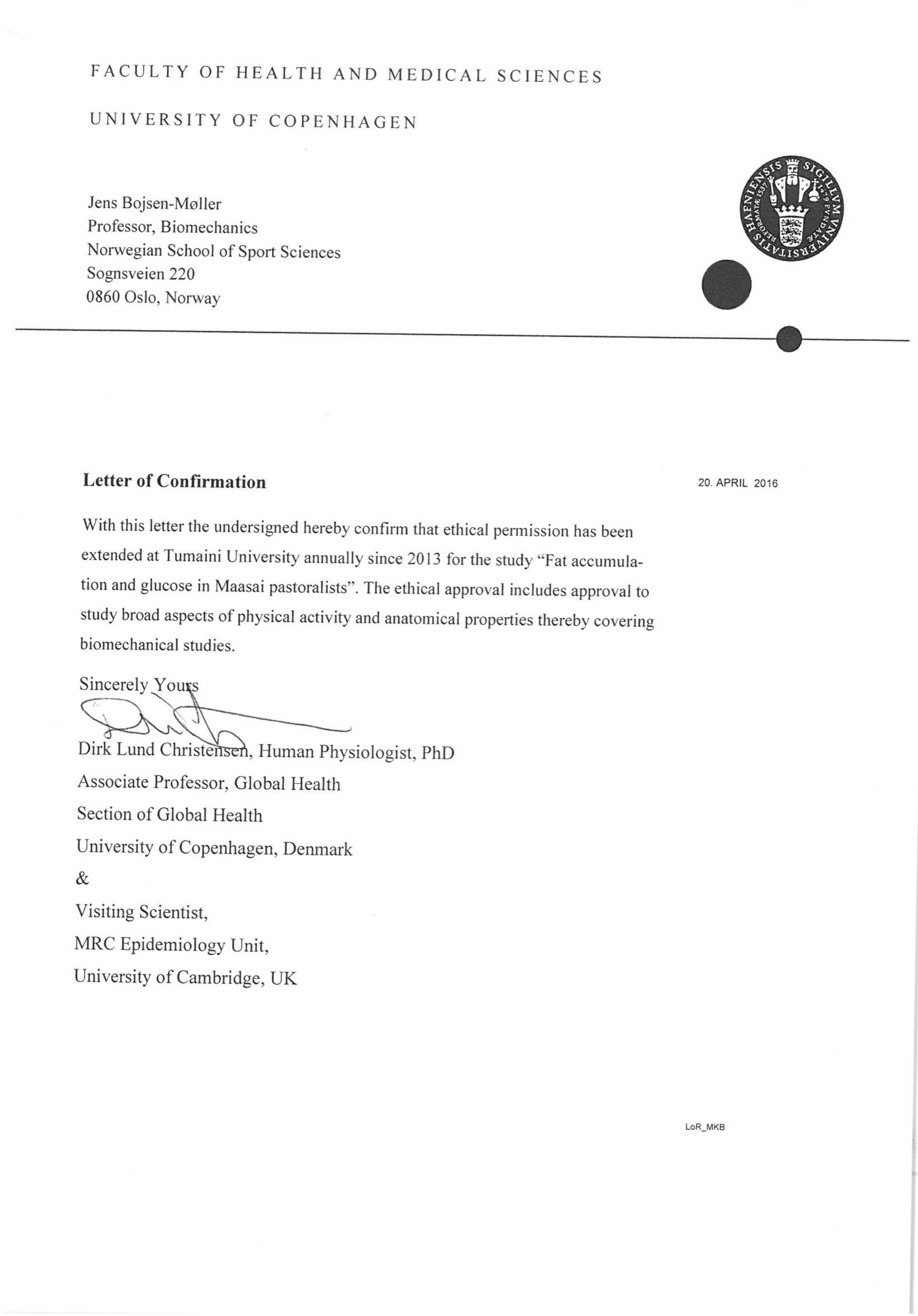
Institution (s): KILIMANJARO CHRISTIAN MEDICAL UNIVERSITY COLLEGE AND UNIVERSITY OF COPENHAGEN

The Proposal was approved by on: 28TH AUGUST,2012

Duration of Study: FROM: 28TH AUGUST,2012 TO 28TH AUGUST,2013

Name: BEATRICE Z. TEMBA
Signature……………
Research Administrator – CRERC

Name : PROF.FRANKLIN MOSHA
Signature……………
Chairman – CRERC



FACULTY OF HEALTH AND MEDICAL SCIENCES

UNIVERSITY OF COPENHAGEN

Jens Bojsen-Møller
Professor, Biomechanics
Norwegian School of Sport Sciences
Sognsveien 220
0860 Oslo, Norway

Letter of Confirmation

20. APRIL 2016

With this letter the undersigned hereby confirm that ethical permission has been extended at Tumaini University annually since 2013 for the study “Fat accumulation and glucose in Maasai pastoralists”. The ethical approval includes approval to study broad aspects of physical activity and anatomical properties thereby covering biomechanical studies.

Sincerely Yours

Dirk Lund Christensen, Human Physiologist, PhD
Associate Professor, Global Health
Section of Global Health
University of Copenhagen, Denmark
&
Visiting Scientist,
MRC Epidemiology Unit,
University of Cambridge, UK

LoR_MKB