DISSERTATIONES KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

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RAGNAR VIIR

The effect of different body positions and of water immersion on the mechanical characteristics of passive skeletal muscle

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To my patients
To new mobile generation
To our daughters and sons

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LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following original papers, which will be referred to in the text by their roman numerals indicated below:

I. Korhonen RK, Vain A., Vanninen E, Viir R, Jurvelin JS. Can mechanical myotonometry or electromyography be used for the prediction of intramuscular pressure? *Physiological Measurement*, 2005, 26: 951–963.

II. Viir R, Laiho K, Kramarenko J, Mikkelsson M. Repeatability of trapezius muscle tone assessment by a myometric method. *Journal of Mechanics in Medicine and Biology*, 2006, 6: 215–228.

III. Viir R, Virkus A, Laiho K, Rajaleid K, Selart A, Mikkelsson M. Trapezius muscle tone and viscoelastic properties in sitting and supine positions. *Scandinavian Journal of Work Environment & Health Supplement*, 2007, 3: 76–80.

IV. Viir R, Vain A, Virkus A, Rajaleid K, Selart A. Skeletal muscle tone characteristics in upright, supine and partial water immersion conditions. *Proceedings of the 57th International Astronautical Congress*, 2006, 1: 132–141.

The contribution of the dissertant to the compiling of the doctoral thesis:

Paper I. The dissertant conducted the experimental part of the studies, had responsibility for collecting and analysing data, as well as outcome assessment and participated in the writing of the paper (the chapters of results and discussion have been written by the dissertant independently).

Papers II, III and IV. The dissertant conducted the experimental part of the studies, had responsibility for protocol development, outcome assessment, data analysis and wrote the manuscript.

ABBREVIATIONS

a_{max}	Acceleration, characterizes the resistant force of the tissue [m/s^2]
a_3, a_5	Accelerations [m/s^2]
BMI	Body mass index
BR	Horizontal bed rest
C	Stiffness [N/m]
CI	Confidence interval
CNS	Central nervous system
CR	Coefficient of repeatability
CS	Compartment syndrome
decr	Decrement, none unit characteristic of elasticity
DI	Dry immersion
EMG	Electromyography, electromyogram
f	Frequency [Hz]
FG	Force of gravity
G	Gravity
GP	Gravitational physiology
Gx	Transverse gravitational force
Gz	Longitudinal gravitational force
HDBR	Head down, bed rest
HOWI	Head-out water immersion
Hz	Oscillation frequency unit
ICC	Intra-class correlation coefficient
IV	Intervertebral (disc)
IMP	Intramuscular pressure
kPa	Pressure unit
l	Deformation depth [m]
ln	Logarithmic decrement
m	Mass of the testing end [kg]
MMG	Mechanomyogram
MSD	Musculoskeletal disorder
MUS	Muscoloskeletal system
MVC	Maximal voluntary contraction
N/m	Stiffness unit
NS	Neck and shoulder
PHOWI	Partial head-out water immersion
SEMG	Surface electromyography
SI	Seated immobility
SD	Standard deviation
T	Period [s]
TA	Tibialis anterior (muscle)
UT	Upper trapezius (muscle)
WI	Water Immersion
yr(s)	Year(s)

1. INTRODUCTION

During my long practice in the field of rehabilitation medicine I noticed that patients severely ill with rheumatic disease could gain significant relief from pain, swollen joints and general muscular tension by being active in quite simple ways. One way was by daily mild exercise done in a pool or hourly when lying down, another by bathing in different liquids such as mud or mineral water (Viir and Eskola, 1990). I also observed by palpation that their trapezius muscle tone changed significantly as they went from a standing or sitting position to a lying position. It came to me that these two observations must be connected, but how?

What is the property of muscle that we feel with our fingers? What is its function? How is it generated and controlled when body posture changes under the force of gravity (G)? How is it related to posture of the body when it is immersed in water? How can these phenomena be described objectively? The main purpose of this study is to address these questions.

Reviewing the literature I found that other researchers have asked similar questions. However this field has only been explored sporadically and several terms are in use that lead to confusion. The properties and functions of skeletal muscle are complex and consist of integrated functions of several structures (Fung et al., 1981, Alway et al., 1988, Bruton, 2002, Roberts, 2002, Schleip, 2003a, b). Muscle tone, also called tension, i.e. the mechanical stiffness and other elastic properties of the skeletal muscles, maintains body posture and assures background tension during muscular activity. Skeletal muscle tone is also responsible for ensuring efficient muscle contraction, as well as for maintaining stance.

Gravitational physiology (GP) is a discipline that explores the effect of gravity (G) and its absence on human physiological systems. It appears that the musculoskeletal system is very properly called a "support and locomotion system" for it must ensure both support and motion. A weightless environment removes the aspect of support. Spaceflight diminishes skeletal muscle tone (Kozlova and Ilyina, 1984, Stein and Gaprindashvili, 1994, Vinogradova et al., 2001). To render a human similarly weightless, a "head down, bed rest" (HDBR) model is often used in studies of GP. Longitudinal (head-to-toe) gravitational force (Gz) is eliminated in this model but transverse gravitational force (Gx) is generated instead, and HDBR at least doubles the number of hours spent per day in the Gx orientation (Adams et al., 2003, Pavy-Le Traon et al., 2007).

Microgravity is even better simulated when a person lies "head out of water immersion" (HOWI) as not only is the Gz eliminated but also the transverse gravitational force is reduced (Gazenko et al., 1987, Pavy-Le Traon et al., 2007). The so-called "dry immersion" (DI) modification of HOWI (Shulzhenko and Vil-Viliams, 1976) where a person is not in direct contact with water but separated from it by a special textile is used by a group of Russian scientists. Partial head-out water immersion (PHOWI) is the model used here (Viir, 2007).

(EMG) is the usual method of measuring muscle function but it depends on the electrochemical potentials generated by the neuromuscular tissue. Therefore it does not directly measure the mechanical properties, or, as many term them, the viscoelastic properties, of such tissue.

Equipment is needed to directly measure changes in the mechanical properties of muscle. Palpation was the earliest, and is still the most common method of assessing muscle tone. Regrettably it is subjective. In order to better understand skeletal muscle tone an objective tool (preferably non-invasive and portable) is necessary. No reliable device to measure the mechanical properties of a muscle at rest or during its contractile activity has been available until quite recently. Instruments that measure only the stiffness of muscular tissue have been described by several authors (Fisher, 1987, Bendtsen et al., 1994, Horikawa, 2001, Leonard et al., 2004, Kato et al., 2004, Arokoski et al., 2005). These instruments assess muscle hardness by measuring the force and speed of a blunt probe when it depresses a muscular surface.

I chose to use a myotonometrical device called the Myoton, developed at the University of Tartu by Dr. Arved Vain. This instrument evaluates skeletal muscle tone the stiffness and elasticity of a muscle by measuring the frequency of its damping oscillation. The Myoton has only been used by a few researchers (Ivanichev et al., 1985, Vain et al., 1992, Vain et al., 1996, Veldi et al., 2000, Bizzini and Mannion, 2003), so I was intrigued by it, though not convinced of its value. As pointed by Bizzini and Mannion, more studies were, and still are, needed to prove this method. The first use of myotonometry was by the inventor of the method, Dr. Arved Vain, in 1992 when he studied rigor mortis. Intramuscular (mechanical) pressure (IMP) can be directly measured inside the muscle (Sejersted et al., 1984, Aratow et al., 1993).

Previously interest had centered on studying tension in the contracted muscle. There had been no systematic study of tension in skeletal muscle, with the accent on the resting state, until I started using the Myoton device to study it. Nor had the resting state of skeletal muscle been assessed in relation to simple body position changes under gravity and in the context of seated immobility. Further, the primary effect of diminishing the gravitational load on the tension of the whole musculature of the body immersed in HOWI had not yet been quantified.

As it was my intention to describe the mechanical characteristics of muscle, I used the opportunity to collaborate with the team at Kuopio University in a study in which the direct invasive measure of intramuscular pressure was conducted simultaneously with EMG, and with myotonometry on my part. We had the opportunity to compare myotonometry with EMG and IMP, again with the emphasis on muscle contraction, to validate the effectiveness of the Myoton.

Then, with the help of colleagues, I measured the effect on muscle tension of changing from a sitting position to a lying position using the upper trapezius muscle as representative of the musculoskeletal support system, as in my clinical practice I had found the changes in this muscle to be the most prominent. The effect of partial head-out water immersion on the mechanical characteristics of the upper trapezius and tibialis anterior muscles was investigated in a special weightlessness simulation ergo-tub facility (Viir, 2007) using the Myoton device and the myotonometrical method.

In the last part of the study, the experimental data I had gathered, plus generalisation from data published by other scientists, led me to better characterise the influence of seated immobility and of water immersion on the functioning of skeletal muscle, highlighting characteristics like muscle tension, stiffness and elasticity. The force of gravity is postulated as a major cause for the observed changes in muscles.

All this might seem like studying the blindingly obvious. But the truly surprising thing is this. Until I became interested in the variation of the tension in resting muscle in different body positions, and under immersion, and sought to find ways to quantify these variations, there had been no such measurements in this area. This has only become possible with the development of enabling technology developed by Dr Vain with input from myself (Vain and Viir, 2000, Viir and Vain, 2001a, Viir and Vain, 2001b).

I believe that the knowledge obtained in the study could be useful in the field of Space Life studies. It could also be helpful in the field of rehabilitation and the prevention of musculoskeletal disorders.

2. REVIEW OF LITERATURE

2.1. Skeletal muscle tone/tension

2.1.1. Historical review

The sense of touch has always been a basic part of human life, both in experience and expression (Evans, 2000). Palpation has evolved from ancient China and Egypt as part of physiological investigation (Walsh and Ashworth, 1997, Knutson and Owens, 2003). It yields qualitative information about skeletal muscle; we can use it to assess the changes in the upper trapezius muscle caused by moving from lying down to standing up (Viir and Eskola, 1990, Viir, 1996, Viir, 1998). However as this is done purely by fingering, assessment can only be reported to the scientific community as subjective, not objective. In any case palpation has a limited capacity to detect different aspects of muscle tone (Walsh and Ashworth, 1997).

Muscle tone has been described, defined and measured in a multitude of different ways. Fenn and Garvey (1934) concluded that tone is not a simple property of muscle rather it is a convenient term including many different properties such as elasticity, viscosity and muscle reflexes. As yet there has been no precise description of this natural phenomenon (Gutnik and Leaver, 2006).

Tension in muscles inevitably has to be involved in holding posture, as stated by Borelli in 1685. From the time of Volta and Galvani in 1700s, the term "tone" has been applied also to the tension produced by muscle contraction stimulated by electrical charge.

The reflex mechanism was originally described in rigid extensor muscles in decerebrated animals. After deafferention, a dramatic drop in muscle tonic contraction occurred in these animals (Sherrington, 1915). This phenomenon was later equated to muscle tone. Reflex muscle tone was assumed to be particularly important to maintain upright posture.

Much effort has been given to detecting the resting muscle tone in normal subjects using electromyography (EMG), for there was a conception that resting muscle tone depends entirely on a low-level tonic discharge of motor neurons resulting in a gentle tonic contraction of muscles (Clemmesen 1951, Ralston and Libet 1953, Basmajian 1957, Basmajian and DeLuca 1985, Walsh 1992, Simons and Mense 1998).

Ralston and Libet stated in 1953: "It has been uniformly observed that, in the relaxed human subject, when s i t t i n g or l y i n g d o w n, there is no detectable persistent background of electrical activity in the many muscles that have been examined in the trunk, limbs and jaws. These muscles are electrically silent unless the individual tenses them."

In 1967 Bernstein stated that a complementary interplay exists between cortical and peripheral levels. According to him, the motor system may be considered as self-organizing, with body elements assembled in response to gravity, surface and other exogenous tasks that are not directly under the control of the brain (Bernstein, 1967). His approach is the precursor to current theories and ideas involving neural and musculoskeletal plasticity, myofascial force transmission, mechanotransduction and to the tensional integrity (tensegrity) theory (Ingber, 1998), all integral to the role of skeletal muscle tone. Bernstein also initiated the use of the term “biomechanics”.

Now that the biomechanical approach to the study of muscles is regaining popularity, it is of interest to note that some of the earliest work in this field was done at this university, then known as the University of Dorpat. In papers published in 1859 and 1873 Professor A.W.Volkmann, the then professor of physiology, pathology and semiotics, stated that good elasticity is needed in healthy muscle for economy in muscular effort (Vain 1999). And in 1868 Professor H.Wassermann, head of the Department of Physiology, published a paper on the thermal effects of stretch and release in skeletal muscle (Feng 1932).

Dr. Ewart Geoffrey Walsh in his charming book “Muscles, Masses & Motion: The Physiology of Normality, Hypotonicity, Spasticity and Rigidity” (1992) eloquently brought out that the mechanics of living systems are as important as the electrics. This profound book has been cited by many authors exploring the challenging topic of muscle tone. The author describes the first attempt at inventing a myotonograph. It was by Angelo Mosso (1846–1910) in 1896. In this technique the patient is seated and a weight and pulley are used to dorsiflex the foot and the resulting elongation of the calf muscles is measured with a scale and pointer. The principle is that as muscle stiffness increased, the displacement at which muscle tension balanced the applied force decreased (Fig. 1A).

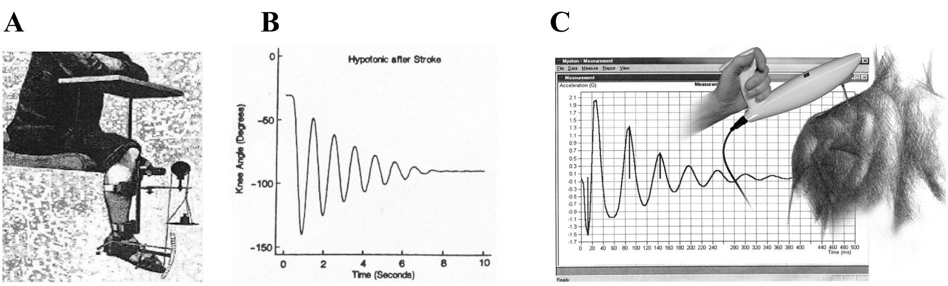


Figure 1. Illustrative presentation of historical view from: A) Mosso’s myotonograph to B) quantified Wartenberg test and C) to modern myotonometry method and Myoton-2 device.

In the Wartenberg test (presented in 1951) the seated patient's legs are lifted to the horizontal, released and permitted to swing freely until they stop. The pendulous movement diminishes steadily and evenly (Fig. 1B). When the oscillation is recorded, it is possible to calculate parameters to characterize this behaviour. However, in certain pathological conditions, the swings are often asymmetrical between legs and greatly reduced. This oscillation approach is similar to the method invented by Dr. Vain in 2000 (Fig. 1C). In this method the subject of the investigation is the tissue that lies beneath the endpoint of the Myoton equipment – muscle tissue mainly, but also skin and connective tissue. While previous methods required a laboratory environment for measurement, the Myoton device, being light and portable is also appropriate for field studies.

Today the relevance of the mechanical properties of intact muscles to the assessment of the skeletal muscle functional state is widely explored. The theoretical views are based on and have been tested by empirical studies. Fischer (1987), Bendtsen et al., (1994), Horikawa, (2001), Arokoski et al., (2005), using hardness meters they developed, calculated the consistency of tissue from the relation between the applied pressure and the depth of penetration. Reliable results have also been published of measurements using a viscoelastometer (Gutnik et al., 2003) and different myotonometers (Fukashiro et al., 2001, 2002; Leonard et al., 2003, 2004; Kato et al., 2004, Kinoshita et al., 2006). Even so, none of these devices simultaneously gives the three parameters: stiffness [N/m], elasticity (reciprocal of the logarithmic decrement of damping of the oscillation), and frequency of the oscillation [Hz].

2.1.2. Definitions for tone

Tonus [tō'nəs] Etymology: Gk, tonos, stretching.

According to Simons and Mense (1998) muscle tone depends physiologically on two factors: 1) the basic viscoelastic properties of the soft tissues associated with the muscle and/or 2) on the degree of activation of the contractile apparatus of the muscle. They also postulate "unnecessary" muscle tension, a confusing intermediate state between muscle contraction that is beyond voluntary control and viscoelastic tension that shows no EMG activity but which can itself at times cause pain.

Muscle Tonus: The state of activity or tension of a muscle beyond that related to its physical properties, that is, its active resistance to stretch. In skeletal muscle, tonus is dependent upon efferent innervation. (Stedman's Concise Medical Dictionary for the health professions (2001) / J.H. Dirckx (Ed) – 24th Edition: Lippincott Williams & Wilkins, Philadelphia)

In Dorland's Medical Dictionary for Health Consumers: *Tonus /to•nus/* (to´nus) tone or tonicity; the slight, continuous contraction of a muscle, which in skeletal muscles aids in the maintenance of posture and in the return of blood to the heart. (Dorland's Medical Dictionary for Health Consumers. © 2007 by Saunders, an imprint of Elsevier, Inc.)

In Merriam-Webster's Medical Dictionary: tonus definition; tone – a state of partial contraction that is characteristic of normal muscle, is maintained at least in part by a continuous bombardment of motor impulses originating reflexly, and serves to maintain body posture called also muscle tone. (Merriam-Webster's Medical Dictionary, © 2007 Merriam-Webster, Inc.)

Definition in Gale Encyclopaedia of Medicine: Muscle tone, also termed tonus; the normal state of balanced tension in the tissues of the body, especially the muscles. (Mentioned in: Contractures in Gale Encyclopaedia of Medicine, Copyright 2008 the Gale Group, Inc)

As a modern concept Masi and Hannon (2008) explain that the human resting muscle (myofascial) tone (HRMT) is the passive tonus or tension of skeletal muscle that derives from its intrinsic (EMG-silent) molecular viscoelastic properties. According to Masi and Hannon HRMT is a passive myofascial property which operates within networks of tensional tissues, i.e., biotensegrity. This passive tension is the CNS-independent component resulting from intrinsic molecular interactions of the actomyosin filaments in sarcomeric units of skeletal muscle and myofibroblast cells. The overarching CNS-activated muscle contractions generate far greater tensions transmitted by fascial elements. Interdisciplinary research on HRMT and its biodynamics promises greater effectiveness of clinical practitioners and productivity of investigators, which warrants priority attention.

In Mosby's Medical Dictionary, 8th edition: 1) the normal state of balanced tension in the body tissues, especially the muscles. Partial contraction or alternate contraction and relaxation of neighbouring fibres of a group of muscles hold the organ or the part of the body in a neutral functional position without fatigue. Tonus is essential for many normal body functions, such as holding the spine erect, the eyes open, and the jaw closed. 2) The state of the body tissues being strong and fit. (Mosby's Medical Dictionary, 8th edition. © 2009, Elsevier)

The fundamental dichotomy in understanding muscle tone, recognised by Bernstein as early as 1967, still exists in definitions of skeletal muscle tone. As the common denominator in all definitions above describing the muscle tone is its tension (created by partial contraction and/or inherent muscle property), for clarity I have decided to use the term "tension" rather than "tone" in the rest of this dissertation, notwithstanding it was not the term used in the original papers. Passive skeletal muscle is defined here as muscle state without voluntary contraction.

2.2. Sources and components of tension, stiffness and elasticity

The precise structural sources of muscle tension have not been established (Neagoe et al., 2003). It is considered that a large contribution to muscle tension, stiffness and elasticity comes from extramyofibrillar structures, particularly from collagen (Kovanen et al., 1984, Purslow, 1989, Gosselin et al., 1998, Ducomps et al., 2003). Helices of collagen fibres, located in the endo, peri, and epimysium of muscle, contribute to the morphology of muscle. We should also consider that as we gather the data about muscle through the skin we must take account of the effect of intra- and extramural aponeuroses, neurovascular tracts, intermuscular septa, deep and superficial fascia, as well as areolar and dense connective tissue, subcutaneous connective tissue and skin itself (Viidik, 1980, Purslow and Trotter, 1994, Iatridis et al., 2003, Huijing, 2007, van der Wal, 2009).

In the last decade biophysical studies of the biomechanics of the sarcomeric third titin-filament system seem to have revolutionized the conception of the role of passive tension in the muscle during contraction, relaxation, stretch, and in passive load-bearing properties (Lieber et al., 2002). Titin is widely recognized as a major contributor to the stiffness of isolated fibres but its contribution to whole muscle stiffness is less clear (Prado et al., 2005, Burkholder, 2007). This titin-filament system contributes to stiffness (and elasticity), and it also maintains the integrity of the sarcomere. Its biomechanical role would seem to have important clinical implications (Horowits et al., 1986, Tskhovrebova and Trinick, 2002, Hackman et al., 2002, Friden and Lieber, 2003, Rankinen et al., 2003). The titin molecule seems also to be a significant component of the support function. Losing it causes a decrease in the stiffness of unloaded fibres, and substantially contributes to the hypogravity muscle syndrome (Vikhlyantsev et al., 2006).

Like all polymeric materials, proteins are viscoelastic, possessing inherent stiffness (and elasticity) (Zhu et al., 2000). Understanding that all complex organisms have important viscoelastic structures may be considered a revolution in biophysics. Elasticity of the musculoskeletal system, on the micro or macro level, is attributable not only to all sarcomeric proteins (including titin and actomyosin complexes) but probably to all cellular and molecular structures, as the response to physical forces is essential to all cells and proteins in the body (Granzier and Wang, 1993, Ingber, 2000, Zhu et al., 2000, Tskhovrebova et al., 2005, Burkholder, 2007).

It has been shown that fragments of titin molecules are also found in the chondrocytes of articular cartilage (Schwarz et al., 2008). Elastic structures probably enable the chondrocyte to better distribute local compressive load and to withstand the swelling pressure coming from inside the tissue (Maroudas, 1976, Bader et al., 1992, Mow and Guo, 2002). It has been proposed that the passive stiffness of a titin spring-like element in chondrocytes, as in skeletal muscle, may help the cell to withstand deformation and to restore its original shape (Schwarz et al., 2008). The passive elasticity of the same titin-filament system gives the diaphragm power to recoil (Moore et al., 2006). Recently, myocardial elasticity has been seen to play an important role in the Frank-Starling heart pumping mechanism (Fukuda and Granzier, 2004). The elasticity of intervertebral discs restores our height every night (Nachemson and Morris, 1964, Yu, 2002) and the loss of elasticity in spinal entheses seems to be an important feature in developing ankylosing spondylitis (Masi and Walsh, 2003). Even bones are elastic to a degree because the fibres of their most abundant collagen protein act against tension, while inorganic material prevents compression (Volkmann and Baluska, 2006).

The property of elasticity might even hinder our untimely ageing (Huq et al., 2002).

2.3. Describing mechanical and bioelectrical characteristics, and intramuscular pressure

Intramuscular pressure (IMP) is inversely related to muscle blood flow and tissue perfusion (Sadamoto et al., 1983, Styf et al., 1987, Järvholm et al., 1988). It is suggested that IMP is related to isometric muscle load (Parker et al., 1984, Järvholm et al., 1988, Järvholm et al., 1989, Sejersted and Hargens, 1995). During isometric loading of the muscle the blood vessels are compressed due to increased IMP. At a critical level of loading, capillary flow may decrease significantly to the point where the metabolism of the muscle tissue can be significantly reduced. This state is called the compartment syndrome (CS) and is associated with pain and fatigue in affected muscles.

It has been documented that EMG can have either a linear (Komi, 1973, Perry and Beckey, 1981) or a non-linear (Lawrence and De Luca, 1983, Solomonow et al., 1986) relationship to muscle load. This relationship may be specific to the muscle and to whether the contraction is eccentric, concentric or isometric. The change in EMG amplitude during sustained isometric loading depends on the relationship between motor unit activity and conduction velocity of the muscle fibre membrane (Krogh-Lund and Jorgensen, 1991, Crenshaw et al., 1997). It has been suggested that EMG amplitude (and IMP) tends to increase during sustained isometric contraction up to fatigue (Krogh-Lund and Jorgensen, 1991, Crenshaw et al., 1997).

It may be that the changes in EMG are due to metabolic alterations in the muscle, specifically when the contraction level is greater than 45% of the maximal voluntary contraction (MVC) (Brody et al., 1991, Crenshaw et al., 1997). At below 30% MVC, changes in EMG are mainly due to neural changes (Krogh-Lund and Jorgensen, 1991, 1992; Crenshaw et al., 1997). Muscle blood flow is highly dependent on metabolic factors during sustained isometric contraction (Crenshaw et al., 1997). While IMP is also related to tissue perfusion it would be useful to investigate IMP and EMG parameters simultaneously to assess their interdependency.

The mechanical properties of muscle are important. The functional state of skeletal muscle is reflected by muscle tone (tension), an indicator of its mechanical stiffness and elasticity (Vain, 1994). EMG shows the electrical activation of muscle and reflects how the nervous system affects the neuro-muscular strategies (Hebert et al., 1995). The amount of activation is reflected in muscle tension, measurable by myotonometry (Bizzini and Mannion, 2003, Gavronski et al., 2007). Also, metabolic processes may affect mechanical and electrical characteristics of muscle, resulting in manifestation of IMP and CS (Styf et al., 1987, Brody et al., 1991, Crenshaw et al., 1997). As EMG and myotonometry parameters are shown to be interrelated (Bizzini and Mannion, 2003), IMP may well be estimated from those parameters.

2.4. The support function in everyday life

The force of gravity is the force of attraction that acts between all objects because of their mass. The Earth's gravity has been fairly constant throughout the evolution of humans from quadrupedal to bipedal locomotion. The action of this force on our bodies we call our weight. An object on the Earth's surface experiences a downward force due to gravitation (Primack, 2004). On Earth every activity is carried out in the gravitational environment. It is accepted that, in people with venous insufficiency, this force can cause oedema or swelling through the gathering of water in the tissue of their legs.

The human being is quite an extraordinary mammal in that during the whole of life, we twice each day change the normal direction of our longitudinal axis relative to the most significant environmental factor – the force of gravity. During our waking hours our spine is roughly along a radius of the Earth, i.e. vertical, and thus has to be supported against gravitational force for us to stay upright. Asleep, we lie horizontally so there is less need for muscular support of the spine. Humans spend about one third of their lifetime horizontally – sleeping. It is the natural way to recover fitness for the next day.

If we were to imagine viewing the whole of a human life as a one-hour movie, the most noticeable bodily activity would be the recurring change between standing upright, sitting semi-upright and lying horizontal. Observed from outer space, this behaviour might well be considered a major aspect of our physiology.

Recently the role of mechanical tension in skeletal muscle adaptation to different physiological and non-physiological demands and conditions has been getting more attention. The temporal changes of constant or intermittent active and/or passive tension are seen to be one of the fundamental determinants of muscle adaptation to loading (Toigo and Boutellier, 2006). Also, oxygen supply to skeletal muscle is influenced by the magnitude of active and/or passive tension that is generated during exercise as well as by the modality of exercise (Vedsted et al., 2006). The magnitude of active and/or passive tension dictates the extent to which blood flow is reduced (Toigo and Boutellier, 2006).

It is difficult to precisely assess the role and influence of the musculoskeletal support function in on our daily life here on Earth within a constant 1G environment. While the locomotion function is widely studied, the support function gets almost no attention. At the same time it is clear that the support function and the macro structures of human body are interdependent. For example, in the course of the waking day human height shrinks by approximately 1–1.5cm, it is a noticeable mechanical measure of the daytime tiring of the musculoskeletal system; also human height tends to decrease with aging. Whereas in Space a person's height increases by up to 5–6 cm (Murthy and Hargens, 1992, Sayson and Hargens 2008). By inference, connective tissue, cartilage tissue and muscle tissue play crucial roles in such phenomena.

2.5. The supportlessness model

For life on Earth the force of gravity is clearly one of the most important environmental factors. In Space flight, environmental conditions are completely different. Transition from 1G on Earth to near zero-G in Space brings a state of weightlessness to an astronaut's body. Weightlessness does not require our support systems to resist the force of gravity. Dramatic changes in bone and muscle tissue occur within the systems that support us on Earth in standing and sitting. Removal of gravity immediately deactivates the postural maintenance system, including its muscle tension. Changes in muscle metabolism occur, leading to muscle atrophy. Loss of bone and muscle tissue is drastic both in its amount and in its speed (Oganov et al., 1992, Desplanches, 1997, Fitts et al., 2000, di Prampero and Narici, 2003, Buckey 2006). Deconditioning of the cardiac muscles may result in decreased pumping capacity of the heart and arterial pressure (Perhonen et al., 2001). Cephalad fluid shifting, with resultant facial puffiness, nasal congestion and headache, neurovestibular disturbances, and a general malaise termed "space sickness" are experienced by astronauts soon after arrival in microgravity (Aubert et al., 2005). Various parameters of immune function are altered in humans during and after space missions (Sundaresan and Pallis, 2008). Earth-based common low back pain (LBP) also is common in spaceflight (Wing et al., 1991, Sayson and Hargens 2008) and the astronauts have the risk of IV disc injury immediately following spaceflight (Johnston et al., 2010).

Down on Earth, disuse of the support and locomotion system, and aging processes share many of the symptoms seen in astronauts during spaceflight. These include orthostatic hypotension, reduced cardiac function, and increased urinary supersaturation of renal chemicals and decreased urinary output, bone demineralisation, muscular atrophy, and neurovestibular symptoms and reduced immune response. It is possible that some of the physiological adaptations seen in aging and disuse may have a physiological basis in common with the changes seen in spaceflight (Sugiyama et al., 1993, Mano, 1996, Miwa et al., 1996, Biolo et al., 2003, di Prampero and Narici, 2003, Ingber, 2005). The mechanical load from gravity may be a strong factor behind the process of ageing and behind several pathological states (di Prampero and Narici, 2003, Vernikos and Schneider, 2010).

Due to the influence of microgravity significant physiological alterations are seen in single cell prokaryotes and eukaryotes, as well as in animal tissues. Basic cellular functions, such as electrolyte concentration, cell growth rate, glucose utilization and bone formation, response to growth stimulation, exocytosis and, endothelium damage and endothelium-dependant microcirculation are all modified in microgravity (Ingber, 2003, Sundaresan and Pallis, 2008, Navasiolava et al., 2010).

Obviously weightlessness presents the ideal environment for studying the effect of mechanical loading on the functioning of skeletal muscle, but spaceflight is extremely expensive. However Earth-based weightlessness simulation models can be used to reveal the important role of gravity to health (di Prampero and Narici, 2003).

On Earth lessening the longitudinal gravitational load is the key approach. Horizontal bed rest (BR) or head-down bed rest (HDBR) conditions are used as models to simulate weightlessness. Measuring skeletal muscle tension, stiffness and elasticity in standing or sitting versus supine position are in line with this approach. Water immersion reduces the support function even further, presumably by also reducing the transverse to human body gravitational force acting on a human from chest to back when lying supine (Pavy-Le Traon et al., 2007).

A study by a group of Russian researchers showed that muscle tone (tension) decreases even more quickly in the water immersion model (WI) than in the bed rest model (Shenkman et al., 1997, Kozlovskaya, 2003). They measured postural soleus muscle tone (tension) by autoresonant vibration (Timanin 1989), defined muscle tone (tension) as transverse stiffness, determined by the magnitude of tissue resistance to deformation from a constant pressure (Timanin 1989, Gallasch and Kozlovskaya, 1998); and expressed their results in pressure unit (kPa). In my research, myotonometrical measurement of the effect of partial WI on upper trapezius and tibialis anterior muscle expresses muscle tension in Hz and stiffness in N/m.

2.6. Sitting and immobility

Sitting is normal and comfortable for many duties and leisure time interests. However, wherever this happens to be – at work (Fig. 2), at home, in the car etc. – prolonged sitting, or being sedentary, has been associated with several serious health problems**.** The word “sedentary” is used by Booth et al., (2002) to describe people who don’t walk briskly for at least thirty minutes each day and are sitting too much. Diseases of comfort are predicted to be the primary cause of death in the 22nd century, but are so already in our 21st century (Choi et al., 2005). For example Pekarski (2004) explains essential hypertension as adaptation to increased gravitational stress caused by habitual prolonged sitting. These general problems have drawn the attention of clinicians and researchers in rehabilitation and preventive medicine (Homans, 1954, Ariëns et al., 2001, Manson et al., 2002, Hu et al., 2003, Brainin, 2003, Beasley et al., 2005, Levine et al., 2005, McGrath, 2007, Manohar et al., 2009, Owen et al., Straker et al., 2009,Bak et al., 2010, and many others).

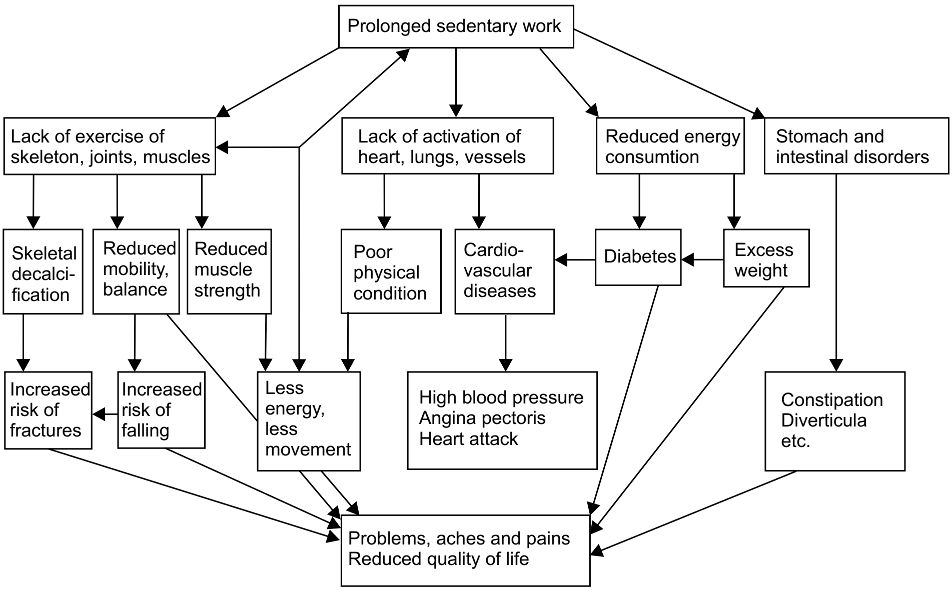


Figure 2. Theme Computerwork- Prolonged and constrained sedentary work (adapted from National Institute for Working Life, Stockholm, 2007 http://www.arbetslivsinstitutet.se/datorarbete/stillasitt_en.asp)

The term Seated Immobility is used to describe one cause of deep venous thrombosis (Beasley et al., 2005). Seated immobility can be lethal. For some time now thromboembolism caused by long-distance flight has attracted medical attention. It is very interesting that during the London Blitz thromboembolism among elderly women, seated for long hours in shelters, was frequent enough to be noticed by doctors. The introduction of bunk bed shelters enabling them to lie down significantly reduced this form of death (Simpson, 1940).

The prolonged use of a visual display can cause "eThrombosis" (Beasley et al., 2003). A doctor of forensic medicine, Lee, reports of a 20-year-old Korean man dying of a thromboembolism after 80 hrs of sitting in front of a computer display screen. Dr Lee warns that, whereas our modern society is extremely concerned about viruses, worms and other dangers in our computers, programs and data, it is not concerned enough about human behaviour in interactions with display screens as a factor with potentially serious consequences (Lee, 2004).

In many cases, working in a seated position involves concentrated visual tasks and highly controlled movements of the hand and fingers. This coordinated movement of head and distal parts of our upper extremities (e.g., in using a keyboard) results in overloading of the muscles of the upper body and will increase the probability of musculoskeletal disorders (MSD) (Pascarelli and Hsu, 2001).

In a study of 25,000 office workers a significant relationship between the duration of daily computer use and physical symptoms was found by Nakazawa et al., (2002) who proposed reducing computer work time to less than 5h per day. A significant association is shown between prolonged sitting at work and neck pain (Kamwendo et al., 1991, Skov et al., 1996, Cagnie et al., 2007). Indeed there is an increased risk of neck pain for people who spend more than 95% of their working time seated (Ariëns et al., 2001). All this knowledge, supported by clinical data, offers an astoundingly simple strategy for healing – the elimination of the primary cause, seated immobility.

DNA telomere shortening has been associated with untimely ageing, though it is too early to say whether this shortening is a cause or an effect. Regular physical activity has been commonly advocated as an approach to reduce the effect of ageing on human neuromuscular function (Booth, 1994; Rantanen et al., 1997; Roubenoff and Hughes, 2000). Age-related decrease in muscle function is associated with a sedentary lifestyle among middle and older aged people (Vandervoort, 2002). Recent study has found more significant change in DNA telomere structures in people leading a sedentary lifestyle (Cherckas et al., 2008).

Until now the expression “sedentary behaviour”, or “sedentary lifestyle”, has, perhaps misleadingly, been used as a synonym for not exercising. Owen (2009) and Bak et al. (2010) have raised the possibility of a new paradigm – the physiology of inactivity. They argue that sedentary time should be defined as the duration of muscular inactivity rather than of the absence of exercise. Seated immobility is not only distinct from a non-exercising style of life, but it also restricts overall physiological activity in daily life. It has been demonstrated that even fidgeting while seated is better than sitting motionless, and is associated with quantitatively significant changes in energy expenditure (Cardon et al., 2004).

There are new suggestions that, independently of moderate to vigorous physical activity, prolonged sitting is strongly associated with obesity (Jakes et al., 2003), abnormal glucose metabolism (Hu et al., 2003, Dunstan et al., 2004), metabolic syndrome (Bertrais et al., 2005), cardiovascular disease and total mortality (Katzmarzyk et al., 2009). Obese individuals spend 2 hours longer per day seated than lean individuals. This is why it is important to understand the physiology of seated immobility for it seems to have a strong effect on overall weight gain in society generally (Levine et al., 2000, 2006). Interestingly, lean individuals spend more time lying down than obese individuals (Levine et al., 2000). One might speculate that spending time horizontally is important to recover from too much sitting!

The upper trapezius muscle in a sedentary subject is one of the most investigated of human skeletal muscles. Musculoskeletal disorders in the neck and shoulder area are a major occupational concern in European countries. They have been a target of three high-level interdisciplinary study projects: Surface EMG for Non Invasive Assessment of Muscles (SENIAM), Prevention of muscle disorders in the operation of computer input devices (PROCID), and Neuromuscular assessment in Elderly Workers (NEW). The latter targeted this problem specifically among elderly females because of their increasing participation in the workforce.

The NEW project focused on the non-invasive assessment of muscle properties, extracting information from the electrical (electromyogram – EMG) and mechanical (mechanomyogram – MMG) signals generated by muscle contractions, with the intention of using this information in the fields of evidence-based rehabilitation, sport and space medicine. The trapezius muscle was of particular interest with the focus on neck and shoulder (NS) pain and tightness. Sjøgaard et al., (2006) reported that NS-cases were characterized by lower MVC and EMG activity than NS-controls, but the study was unable to reveal quantitative EMG indicators and functional tests that could objectively assess disorders in neck and shoulder area, and thereby increase understanding of NS disorders mechanisms. So, neither EMG nor MMG are effective tools to characterise the function of muscles in a static sitting position as this position evidently does not require a significant level of neuromuscular activity.

Among seated video display unit (VDU) users, subjectively perceived muscular tension has been shown to be associated with an increased in risk in developing neck pain (Wahlström et al., 2004). This article was strongly criticized by Punnet (2004). Punnet argued that the term – subjectively perceived tension – was not defined to the readers, for subjectively perceived tension may have multifactor cause(s) – e.g. physical and/or psychosocial, reflections of occupational and/or non-occupational stressors.

Therefore, to avoid subjectivity, objectively quantified data of muscle tension is needed. The importance of objectively characterizing the mechanical properties of muscles in the seated position is also recognised by Bak and colleagues (2010). This study is designed to resolve some of these issues.

3. OBJECTIVES OF THE STUDY

The general aim of the study was to gain a better understanding of muscle function in supporting the human body against the gravitational load assessing muscle mechanical characteristics in different positions and under various conditions with the myotonometry method.

More specifically, the present study had the following objectives:

1. To examine the relationships between the intramuscular pressure and the mechanical and electromyographic characteristics of the dorsal forearm extensor and the anterior tibial muscles (Study I).
2. To verify the reliability and repeatability of the myotonometric method in describing the mechanical characteristics of the upper trapezius muscle (Study II).
3. To assess the effect of changing from lying to sitting and standing on the mechanical characteristics of the upper trapezius muscle (Study III).
4. To assess the effect of partial water immersion on the mechanical characteristics of the upper trapezius and anterior tibial muscles (Study IV).

4. MATERIALS AND METHODS

4.1. Subjects

In total 57 female and 15 male subjects gave informed consent and participated in this study. The study was approved by the Ethical Committee of the Päijät-Häme Hospital District and the Ethics Committee for Human Studies of the Tartu University. Table 1 gives the types of the subjects and their anthropometric characteristics in the different studies.

Table 1. Anthropometric characteristics and age of the subjects (mean ± SE).

Studies	n	Age (yrs)	Height (cm)	Body mass (kg)	BMI ($kg \cdot m^{-2}$)
Study I (Paper I)					
Men	15	45.8±10.0	177.8±5.2	86.0±6.6	27.3±2.9
Women	22	40.3±11.5	163.8±4.2	64.5±10.3	24.9±4.0
Study II (Paper II)					
Women	20	44.2±14.7	165.9±6.8	66.1±11.5	25.8±3.6
Studies III–IV (Papers III–IV)					
Women	15	27.0±3.5	168.0±6.0	55.6±5.6	20.8±2.7

Note: BM – body mass; BMI – body mass index; MSD – musculoskeletal disorders.

All subjects in Study I had pain in the dorsal forearm or anterior leg and were suspected to have the compartment syndrome (CS) there. Intramuscular pressure (IMP) measurements in Study I were conducted according to the clinical protocol in use at the Kuopio University Hospital. In Study II fifteen employed women with various musculoskeletal disorders took the rehabilitation course at the Rheumatism Foundation Hospital Heinola. The 5 women participants from the hospital staff were healthy. In Studies III and IV fifteen healthy right-handed young female computer operators participated.

4.2. Study design

The present multicenter study was carried out from 2004 to 2007. This dissertation describes four studies. The first part covers the validation of the methodology of myotonometry in respect to electromyography and intramuscular pressure recording, and its interobserver repeatability. The second part covers the assessment and exploration of the role of the mechanical properties of skeletal muscle in different body positions and in partial water immersion under the force of gravity. The first part describes work done in Finland, the second part in Estonia.

Study I was carried out in the Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital and the University of Kuopio, Finland. Combined IMP, EMG and myotonometry measurements were carried out on the dorsal forearm (extensor compartment) or the anterior leg (anterior tibial compartment) during short-term and long-term isometric loading in 37 subjects who had pain in these compartments respectively. The interrelationships between IMP, EMG and myotonometry were studied.

Study II was carried out in the Rehabilitation Centre of the Rheumatism Foundation Hospital, Finland in cooperation with the Department of Musculoskeletal Medicine, Medical School, University of Tampere, Finland. During the testing session the subject was in a comfortable relaxed sitting position supported by a backrest, with arms resting in the lap. For all subjects the same simple wooden chair with four legs was used. It had an upholstered seat and backrest but neither armrests nor height adjustability. The subject was asked to focus her visual attention on a spot at a distance of 2 metres to maintain the gaze and the neck angle in the same position for the whole session. Nontoxic marks were made on the skin above the middle of the upper trapezius muscle belly halfway between the acromion and the seventh cervical process. Then the myotonometric device was applied to the marks, and twenty consecutive measurements (with a time interval of 1–2 seconds between each) were made on both sides by the two investigators alternately within the same session, lasting from 5 to 12 minutes. The average values from each of the 20 consecutive measurements were used for further data analysis.

Study III was done in two steps in the Laboratory of Kinesiology and Biomechanics, Institute of Exercise Biology and Physiotherapy, University of Tartu. In step 1 the subject was in a comfortable relaxed sitting position as in the Study II and a myotonometric device was used for the measurements of the upper trapezius muscle on both sides of the body. In step 2, the same measurements were taken, but, in this case, the participant lay comfortably supine on a padded examination table. For each participant, the measurements of each step were done sequentially, lasting 8–10 minutes overall, including 3 minutes of horizontal positioning and relaxation between steps 1 and 2.

In Study IV two muscles were measured under the following conditions: the UT muscle – in standing upright, semi-upright sitting, and lying positions and in lying supine and partially immersed in thermoneutral 34.5º water; the TA muscle – in lying supine and partially immersed in thermoneutral water 34.5º In lying positions a specially developed ergonomic tub was used. Its bottom curvature gave continuous posterior contact and support, with the legs slightly flexed at the hips and knees. The tub was also built for relaxation procedures in physical therapy and it could be filled with water up to the temporo-mandibular joint, leaving the distal phalanxes of the toes under water. While lying in this tub, the head is placed higher than the rest of the body, so when filling the tub the body will start to lose weight before the head. In this study, the tub was only partly filled, so that the water only reached up to where the occiput met the tub's surface (Fig. 9B). In this state the test subjects felt slightly relieved from the effect of gravity while still just being in posterior contact with the bottom of the tub. Introducing the thermoneutral water took about 2–3 minutes (with much the same delay between the measurements). To reduce the possible effect of differences between the room and the water temperatures, the tub was warmed with the thermo-neutral 34.5º water before the test.

The test protocol consisted of 20 consecutive (so called Multi-scan) measurements for the muscles on both sides of the body in each of the positions and conditions. The full myotonometric data set therefore consists of 20 measurements each in standing, sitting, lying dry and lying in partial WI for the left and right UT muscles (160 data points) and in lying dry and lying in partial WI for the left and right TA muscles (80 data points).

4.3. Methods

4.3.1. Myotonometry

The mechanical characteristics of the skeletal muscles were recorded by a damped oscillation method using the hand-held myotonometers, Myoton (in Study I), Myoton-2 (Study II) and Myoton-3 (Studies III and IV) (Figs. 1C, 3, 4 and 9). All three generations of Myoton have been calibrated to give consistent data. The first generation Myoton uses lower digitalisation frequency, but the test results have been consistent. Latter Myotons differ also in terms of improved user interface. Myoton devices are manufactured by Müomeetria Ltd, Estonia. Myotonometers weigh 0.4 kg and use a compatible PC.

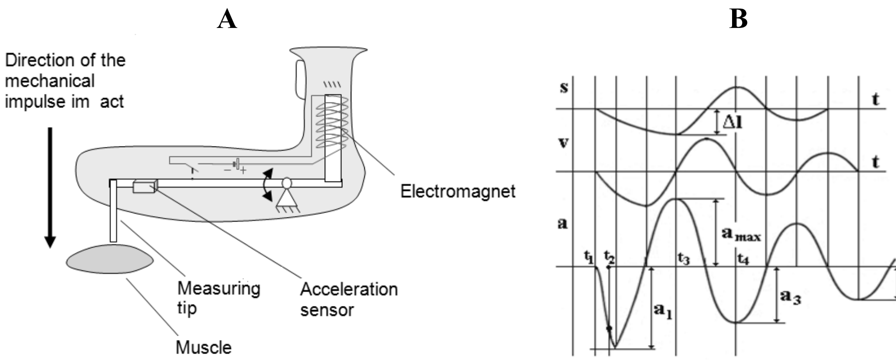


Figure 3. A) A schematic representation of the Myoton device, which in principle gives the muscle under investigation a dosed local mechanical impulse shortly followed by a quick release, and records the mechanical response of the muscle. B) Waveforms of acceleration (*a*), velocity (*v*), and displacement (*s*), of the damped natural oscillation performed by the myotonometer probe are presented (b).

The myotonometer works as follows. The testing end is placed on the surface of the skin overlying the muscle under investigation, and perpendicular to it. A slight downward pressure is exerted on the soft subcutaneous tissues by the weight of the probe, slightly compressing them, their usual stiffness being small compared to the stiffness of the muscle.

When the device is switched on, its electromagnet produces a short (few milliseconds) impulse of constant force, which is passed via the probe to the contact area. This causes the tissue under the probe to be deformed for a short predetermined period. When the current to the electromagnet is stopped, the probe is freed to move, and the muscle and the probe perform damped natural oscillations together, governed by the elastic properties of the biological tissue. An acceleration transducer on the probe allows the muscle deformation characteristics to be determined from recorded details of the oscillations.

The acceleration $a_{\max}$ at the point of maximum compression of the muscle under investigation characterizes the resistive force of the tissue (= $ma_{\max}$, where m is the mass of the probe) for a deformation depth l, and the ratio $C = ma_{\max}/l$ [N/m] describes the stiffness of the tissue.

The theory of mechanical oscillations gives a parameter for the dissipation of the mechanical energy through damping of the oscillation, the logarithmic decrement, $\ln(a_3/a_5)$ which characterizes the elasticity of the muscle under investigation where a_3 denotes the second and a_5 the third positive amplitude of the acceleration curve. The natural oscillation frequency is calculated using the same waveform of the damped natural oscillation as $f = 1/T$ [Hz], where T denotes the oscillation period in seconds.

A B

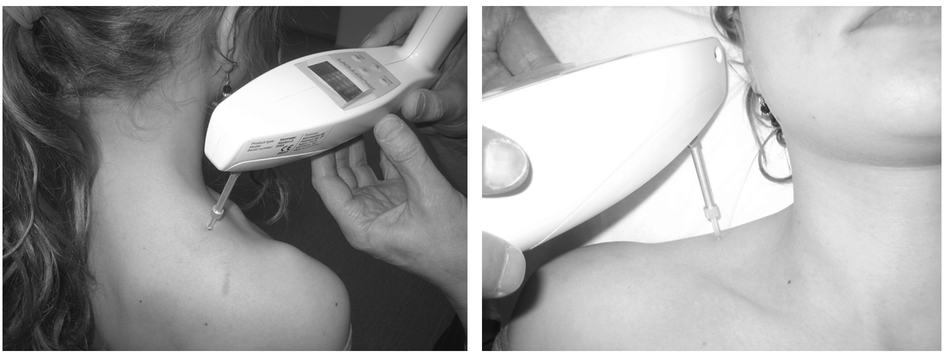


Figure 4. Myotonometric measurement by Myoton-3 device of upper trapezius muscle (UT) in A) sitting and B) lying supine positions (Studies III and IV).

Established parameters

Three parameters were calculated, namely frequency, stiffness, and elasticity. The frequency of the damping oscillation characterizes the state of the tissue under mechanical stress: the higher the frequency (Hz), the tenser the muscle. Muscle tension increases through both contraction and stretching. By definition, the oscillation frequency of inactive muscle is its tension.

Stiffness reflects the resistance of the tissue to the force that changes its shape: the higher the stiffness (N/m), the more force is needed to modify the shape of tissue. During contraction or loading, the stiffness of skeletal muscle increases.

Elasticity is the ability of tissue to recover its shape after contraction, and it is characterized by the (unit-less) logarithmic decrement of the oscillation. It describes how much mechanical energy is dissipated in this damping: the smaller the parameter, the more elastic the tissue. Less elastic tissue dissipates energy more rapidly. The absence of elasticity is plasticity – the body holds the shape it is given.

While electromyography registers the parameters of electrical activity of the skeletal muscle, the parameters produced by the Myoton device reflect the conditions (i.e., the workability restoration time of muscles during work and after it) and the character of mechanical tension transmission from the sarcomere to the bone levers (Vain, 2002).

4.3.2. Intramuscular pressure measurement

Intramuscular pressure (IMP) is a physical property related to the development of force in a muscle. Fluid pressure within a muscle, i.e., IMP, increases linearly with muscle contraction force (Sejersted et al., 1984, Aratow et al., 1993). IMP elevation results from increased muscle fibre tension and therefore reflects the mechanical state within the muscle independent of muscle length and muscle activation. IMP is directly and linearly related to contractile force, but its main research disadvantage is the invasiveness of the way it is measured (Sejersted et al., 1984, Aratow et al., 1993, Ballard et al., 1998). The intramuscular pressure is low in the trapezius muscle during ordinary activities that do not normally impair the local blood flow (Larsson et al., 1993). Intramuscular pressure in this study was measured using an invasive wick catheter (Stryker, Intra-Compartmental Pressure Monitor System, Indwelling Slit Catheter Set, USA) (Bourne and Rorabeck, 1989) (Fig. 6). First, the subject's skin was cleaned carefully and the saline filled catheter was inserted into the muscle compartment of interest using a needle. The needle was pulled out and the hydrostatic pressure of the catheter was led to a pressure detector (AE840, AME, City, Norway) connected to the pressure amplifier (Mingograph 4, Siemens-Elema, City, Germany) to indicate the intramuscular pressure.

Before the measurements, the IMP catheter and EMG electrodes were positioned in the muscle compartment and on the skin surface above the muscle, respectively (Fig. 5).

A B

Figure 5. Placements of EMG electrodes above the skin: A) of the dorsal forearm and B) anterior leg. Active electrodes are gray and ground black. The IMP catheter tip was positioned in the muscle compartment of interest 2–4 cm under the active EMG electrodes. Test location for the myotonometry measurements was between the active electrodes.

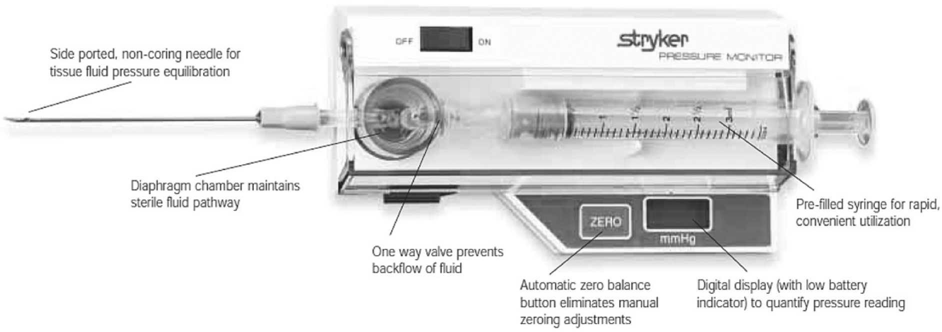


Figure 6. An Intra-Compartmental Pressure Monitor system was used for continuous measurement of compartment pressure.

For the measurements, the subjects were supine and the limb under investigation was loaded with a loadmeter (Digitest force, Digitest OY, Finland). The foot or arm was lying on the bed in a natural position without any extra stretch. Extensor loading and dorsiflexion loading were used for the dorsal forearm and the anterior leg respectively (Fig 7).

A B

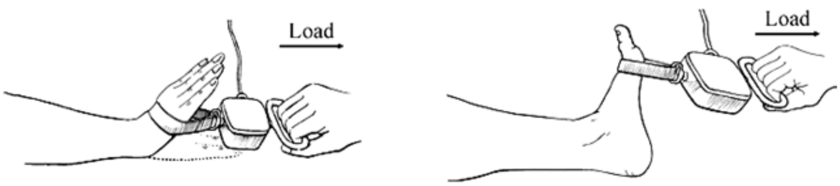


Figure 7. A schematic representation for the isometric loading: A) of dorsal forearm extensor muscles and B) tibialis anterior muscle. Both the wrist and ankle joints were dorsiflexed.

During loading IMP, EMG and myotonometry parameters were measured simultaneously. The standard protocols were used for short-term (5 sec, 0%, 100%, 75%, 50%, 25% and 100% MVC) and long-term (60 sec, 40% and 20% MVC) isometric loading of the muscle. IMP, EMG and load signals were continuously recorded for four minutes, while myotonometric measurements were registered at rest as well as at several times during isometric loading of the muscle.

After amplification the pressure and loadmeter signals were transferred to a PC equipped with a 12-bit A/D converter. The calibration of pressure measurement was made against a sphygmomanometer (Erkameter, Germany), originally designed for the none-invasive measurement of blood pressure. The intramuscular pressure-load analysis was done with a custom-coded PC-program. In addition the raw pressure/time data and the maximum value of IMP corresponding to each short-term load were systematically quantified from the measurements.

4.3.3. Electromyography

A quantitative surface EMG recording was taken simultaneously with IMP and myotonometric measurements. The EMG of the muscle was recorded using bipolar electrodes attached to the skin surface above the muscle of interest, as well as on the corresponding site of the contralateral muscle. The EMG signal was preamplified and sent to an ME3000P Muscle Tester unit with a 2 MB SRAM-card (Mega Electronics Ltd, Kuopio, Finland) The signal was amplified and filtered in the ME3000P unit. The frequency band for the measurement was 15–500 Hz with a sampling frequency 1000 Hz. IMP and load signals were also connected to the ME300P unit via an ME3000 ISO isolation unit. After registration the data from SRAM-card were downloaded to a PC and the analysis was done by the Multi Signal System ME3000P version 2.05 software (Mega Electronics Ltd, Kuopio, Finland). The raw EMG signal was subsequently rectified and averaged by the software using averaging time 10 ms (Fig. 9). To describe the time-dependent behaviour of the EMG and IMP during long-term loading (Fig. 9B) curve-fitting was performed using $y = A_0 + A \exp(-kt)$, where A_0 is the amplitude of EMG (μV) or IMP (Pa) at equilibrium, A is the change of the amplitude, k (s^{-1}) is the time constant and t (s) is time. This exponential best-fit could describe accurately the time-dependent behaviour of both EMG and IMP.

4.3.4. Measurement of the partial Head-Out Water Immersion model

Muscle measurement requires standardisation, and voluntary or involuntary contraction during measurement would invalidate any attempt to measure steady state parameters. So-called passive tension measurements demand the absence of any muscle activity.

There was a need for a device which would simulate weightlessness by using only just enough water to negate the effect of gravity without having the subject floating and therefore inevitably moving. This prompted me to design the transportable Water Immersion facility. While lying in the tub, the bottom curvature of the tub provides continuous posterior contact, but only just, not in a load-bearing manner. Hips and knees are slightly flexed in the same manner as spontaneously happens in Spaceflight weightlessness (Thornton et al., 1974) (Fig. 8).

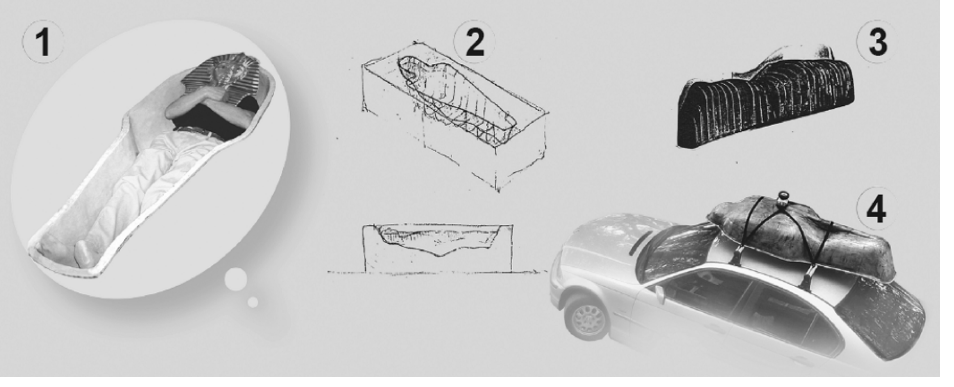


Figure 8. Inspired by 1) ancient Egyptian sarcophagi 2) designs and 3) a wooden model of a novel 4) transportable Water Immersion facility; designed by me and presented at the Technology for Artificial Gravity and Microgravity Simulation Symposium held by The Technical Directorate of the European Space Agency (ESA) 10–12 December 2007 ESTEC Noordwijk, The Netherlands (Viir, 2007).

The test person is lightly supported by the bottom surface of the tub to avoid floating. All the muscles are about the same distance away from the water surface thus avoiding the extra pressure on the legs present in the regular standing or sitting position as, for instance, in the kind of WI tank used in the OSMA Bed Rest project in Japan (Mano, 2008). Dr. Mano and colleagues have most elegantly demonstrated how muscle activity is systematically reduced by increasing the amount of submersion of the upright standing body in HOWI (1985).

A

B

Figure 9. Myotonometric measurements of A) tibial anterior (TA) and B) upper trapezius (UT) muscles in the Water Immersion facility used in study IV.

The gravitational force gradient is more uniform in the position used in this study where BR inactivity is coupled with the probable reduction of transverse G-stress. The head is placed higher than the rest of the body, so that when filling the tub the body will start to lose weight earlier than the head. The tub is partially filled so that the water reaches up to the point of contact between the occiput and the tub's surface. In this condition test subjects feel somewhat freed from gravity while their posterior is still barely in contact with the bottom of the tub. Free floating is avoided so that neck muscles do not become active in trying to maintain the position of the body (Fig. 9). In this position muscles on the front of the body are most easily measurable with the myotonometric device in both steady states (relaxed and voluntary contraction). To explain the different states of the tensed network of the overall muscular system under microgravity and full gravity conditions it is necessary to compare muscles with and without WI.

4.4. Statistical evaluation of the data

Standard statistical methods were used to calculate the means and standard errors of mean (±SE). The between-group differences in mean values were evaluated by using Student's t-test for unpaired data.

Study I

The mean values and standard deviations (±SD) were calculated for the IMP, EMG and myotonometrical values. Linear regression analysis and Bland and Altman analysis (Bland and Altman, 1986) were used to describe the relationships between recorded parameters and best-fit equations, correlation coefficients (r) and p-values were determined using OriginV5.0 software (Microcal Software, Inc., Northampton, MA, USA). The Wilcoxon signed ranks and Mann–Whitney U-tests were used for statistical comparisons.

Study II

The means, standard deviations (SD) and ranges for all the three parameters were generated. Intra-class correlation coefficients (ICC), 95% confidence intervals (CI) and coefficients of repeatability (CR) were calculated to assess interobserver reliability for natural oscillation frequency, stiffness and elasticity. Intra-class correlation coefficients (ICC) and their 95% confidence intervals were calculated using variance component analysis, the ICC expressing the amount of the intersubject variance to the total (the between plus the within) variance. The ICC was calculated for both sides of the subject and the averaged measure was finally found. The ICC value, approximately 1, showed that the variance within the subject, created by the investigator, was negligible. Co-efficients of repeatability showed the expected maximum size of 95% of the absolute differences between paired observations. The Bland and Altman plot method (1986) was used, the aim being to plot the difference on average between the two measurements against the sum. 25 mean values from right and left sides were compared using the t-test.

Study III

The individual measurement results were combined for each position, and a similarity to normal distribution appeared. The results of the Student's t-tests follow. The box-and-whisker plot method (14) was used because it can combine a display of all the data together with a statistical summary, and the concise graphs are easily interpreted. The interquartile range contains the middle 50% of the data and is shown by the length between the outer edges of the box. The whiskers in the box plot extend to the most extreme data point that is no more than 1.5 times the interquartile range from the box (quartiles). Points farther than 1.5 times the interquartile range are plotted individually.

Study IV

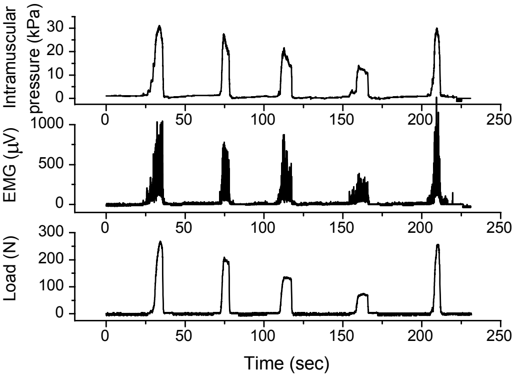
The hypothesis of decrease in values was tested for tension and stiffness between sitting and lying positions as well as for lying and WI conditions. As it is difficult to anticipate the direction of change between the standing and sitting positions as well as any assumption for direction of change of elasticity, only significant change was tested for in those cases. Only differences significant at the 5% level are reported. As the first step, the data were combined over the entire group, and the means of the myotonometric parameters were compared using Student's t-test with equal/unequal variances. The equality of variances was assessed by the Levene test. Secondly, the same analysis was done for each of the test subjects separately, and the results of this were summarised over the whole group, giving insight about the robustness of the results – for how many subjects within the group of 15 each change was significant (individual count). Statistical analysis was performed using SAS (http://v8doc.sas.com/sashtml/) and R (http://www.r-project.org).

5. RESULTS

5.1. Relationship between intramuscular pressure and the mechanical and electromyographic characteristics of the dorsal forearm extensor and anterior tibial muscles

All measurements of IMP, EMG and muscle tension (Paper I) were conducted during rest and standardized short-term (100%, 75%, 50%, 25%, 0% and 100% of the maximum load (Fig. 10A)) and long-term (20%, 40% of the maximum load (Fig. 10B)) isometric loading of the muscle.

A



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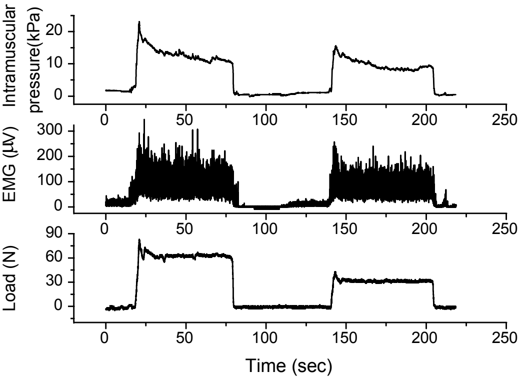


Figure 10. Intramuscular pressure (IMP) and electromyography (EMG) at rest and during A) short (100%, 75%, 50%, 25% and 100% MVC) and B) long (40% and 20% MVC) term isometric contractions.

Mean values of the recorded IMP, EMG and mechanical characteristics of dorsal forearm extensor muscles and tibialis anterior muscle at rest and at maximum load are presented in Table 2.

Table 2. Mean values (±SD) of the intramuscular pressure, EMG, frequency (tension), damping (i.e. reciprocally characterizing elasticity) in forearm extensor muscles and tibial anterior muscle at rest and at maximum load.

	Forearm extensor muscles				***Tibial Anterior muscle***			
	Rest	*n*	*Max load*	*n*	*Rest*	*n*	*Max load*	*n*
Intramuscular pressure *(kPa)*	0.84 ± 0.49	22	11.4 ± 9.5	22	2.26 ± 1.22	17	12.9 ± 8.9	18
EMG *(μV)*	4.76 ± 2.19	15	272 ± 120	14	4.33 ± 2.52	17	362 ± 227	16
Frequency *(Hz)*	15.9 ± 1.7	13	25.4 ± 2.9	13	22.7 ± 3.4	12	31.1 ± 7.5	12
Damping	1.02 ± 0.28	12	1.08 ± 0.23	13	1.01 ± 0.29	12	0.86 ± 0.16	12

Intramuscular pressure, EMG activity and tension (oscillation frequency) were higher in the tibialis anterior muscle than in the forearm extensor muscles. Also, the values of all characteristics were higher at the maximum load compared to values at rest. Experimental recordings (Fig. 10) revealed that intramuscular pressure (IMP), electromyography (EMG) and myotonometrically measured mechanical characteristic of tension (oscillation frequency) were highly linearly related to relative muscle load ($r = 0.819–0.996$) both in dorsal forearm extensor muscles and tibialis anterior muscle. However, only maximum EMG amplitude was significantly related to absolute maximum force of the tibialis anterior muscle ($r = 0.623$, $n = 11$, $p = 0.04$). Damping (i.e. logarithmic decrement of damping oscillation, reciprocally characterizing muscle tissue property of elasticity) was not related to relative isometric contraction force in forearm extensor muscles and tibialis anterior muscle (Fig. 11).

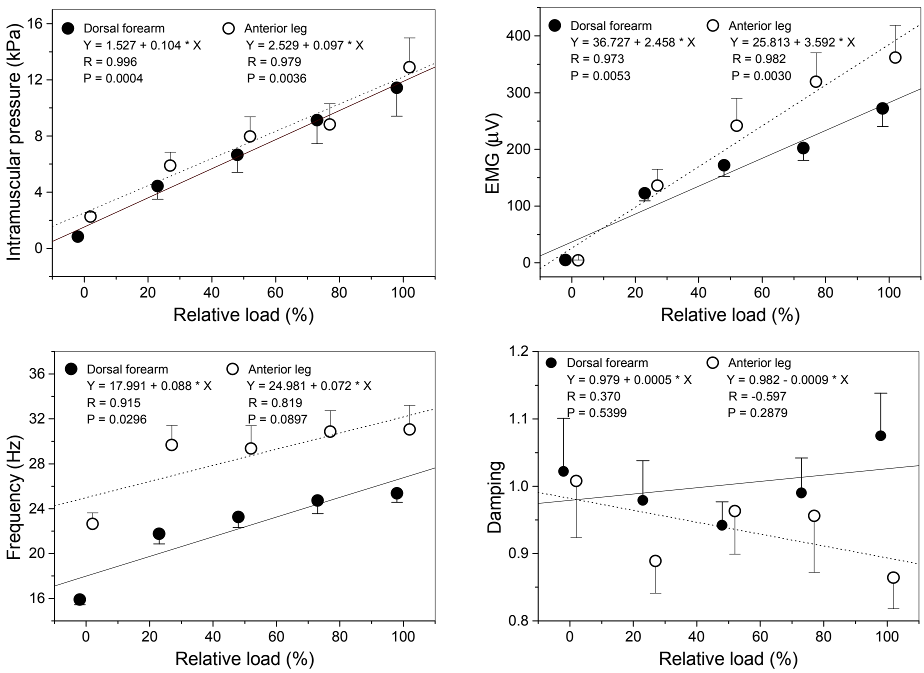


Figure 11. Intramuscular pressure, EMG, tension (frequency) and elasticity (damping) characteristics as a function of relative muscle load (0%, 25%, 50%, 75%, 100% MVC).

Simultaneously recorded electromyography and myotonometry tension characteristics correlated significantly with intramuscular pressure at rest and during loading periods (Table 3).

Table 3. Correlation coefficients between intramuscular pressure and EMG, frequency and damping in dorsal forearm extensor muscles and tibialis anterior muscle.

	Intramuscular pressure			
	Forearm extensor muscles	***n***	***Tibialis Anterior muscle***	***n***
EMG	0.515*	70	0.855*	80
Frequency	0.487*	65	0.773*	65
Damping	0.178	65	–0.109	65

*$p < 0.0001$, n is the number of data points (*e.g.* $n = 70$ refers to 14 subjects).

Reproducibility of all characteristics was derived by comparing the values from recordings during the first and last 100% MVC. Although the values were highly correlated (r=0.805–0.918, n=39–46), the recordings during the last 100% MVC were slightly lower than the recordings during the first 100% MVC. The difference between these values was highest in EMG (Fig. 12).

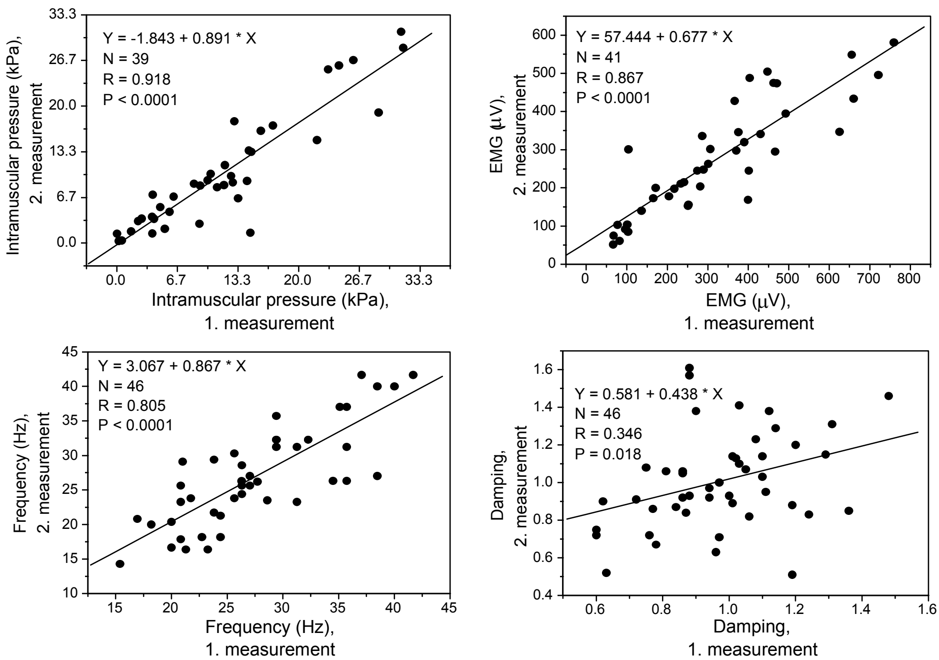


Figure 12. Reproducibility of intramuscular pressure (IMP), electromyography (EMG), tension (frequency) and elasticity (damping) as the second 100% MVC as a function of the first 100% MVC.

For tibialis anterior muscle there were strong positive correlations between tension and electromyographic activity with intramuscular pressure and for forearm extensor muscles moderate positive correlations were established between tension and EMG characteristics with IMP.

5.2. Repeatability of the myotonometrical measurement of mechanical characteristics of the upper trapezius muscle

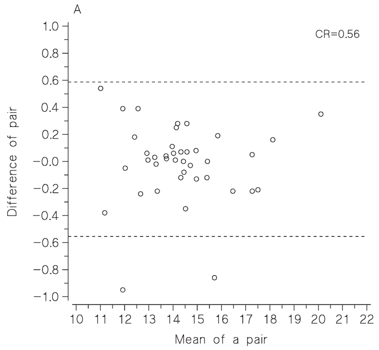
The values of natural oscillation frequency of the upper trapezius muscle, stiffness and logarithmic decrement of damping are presented in Table 4. The results shows that the registered values of the mechanical properties are individually specific, varying remarkably between the tested subjects: (i) 10.7–19.9 [Hz] for natural oscillation frequency, (ii) 0.7–1.4 for logarithmic decrement of damping, and (iii) 135–355 [N/m] for stiffness. The mean values (SD) of the parameters were obtained from the results measured by the first investigator. The mean natural oscillation frequency of both trapezius muscles was 14.4 (1.9) [Hz]. The mean logarithmic decrement of damping was 1.1 (0.2), and the mean stiffness was 218 (51) [N/m]. No statistically significant differences could be found between the mean values measured from the right and left trapezius muscle. The results showed that the myotonometrical method, conducted with Myoton-2 equipment, evidenced good interobserver agreement for assessment of relaxed trapezius muscle tension in this experiment. In the heterogeneous group of twenty women, some healthy and some with musculoskeletal disorders, the stiffness and elasticity of relaxed trapezius muscle varied widely between the tested subjects (see Table 4).

Table 4. Means and (±SD) values of tension (frequency [Hz]), stiffness (N/m) and elasticity (decrement of logarithmic damping of right side upper trapezius muscle registered by two different investigators.

	Frequency [Hz]				***Stiffness [N/m]***				***Logarithmic decrement***			
	Investigator1		***Investigator2***		***Investigator1***		***Investigator2***		***Investigator1***		***Investigator2***	
ID	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
1.	12.89	0.30	12.95	0.27	208.60	9.00	198.20	15.20	0.909	0.069	0.945	0.116
2.	14.43	0.38	14.71	0.48	259.90	7.10	270.10	7.30	1.178	0.063	1.133	0.072
3.	16.58	0.44	16.36	0.57	290.31	7.87	292.31	10.98	1.340	0.050	1.340	0.090
4.	17.38	0.87	17.16	0.48	283.75	13.71	275.80	20.71	1.020	0.080	0.990	0.100
5.	14.54	0.25	14.61	0.28	217.94	11.11	216.64	18.44	0.860	0.050	0.850	0.060
6.	11.73	0.30	12.12	0.30	180.61	5.17	189.39	4.21	1.070	0.060	1.100	0.060
7.	15.03	0.31	14.90	0.54	223.20	13.50	222.30	12.00	1.165	0.079	1.194	0.097
8.	12.36	0.29	12.75	0.23	165.20	9.60	167.60	9.90	1.059	0.063	1.101	0.061
9.	15.46	0.35	15.34	0.36	256.70	10.10	256.10	8.40	1.070	0.053	1.120	0.049
10.	14.09	0.32	14.10	0.25	212.70	11.60	211.90	6.80	1.033	0.054	1.031	0.040
11.	14.91	0.50	14.99	0.33	212.57	8.84	208.70	10.70	0.930	0.090	0.860	0.052
12.	14.69	1.38	14.34	0.46	205.75	19.73	207.20	11.00	1.400	0.110	1.397	0.067
13.	17.24	0.67	17.29	0.82	258.54	23.90	259.82	22.35	1.330	0.080	1.350	0.060
14.	12.05	0.29	12.00	0.48	153.70	8.00	154.00	7.30	1.038	0.040	1.074	0.066
15.	13.31	0.27	13.29	0.17	182.58	5.08	184.84	3.88	0.710	0.030	0.710	0.020
16.	11.37	0.15	10.99	0.24	137.44	6.10	139.68	4.64	0.930	0.030	0.980	0.010
17.	13.23	0.38	13.26	0.84	168.50	6.30	164.80	7.80	1.096	0.078	1.098	0.083
18.	14.29	0.33	14.36	0.48	221.10	14.60	218.24	12.79	1.200	0.100	1.190	0.100
19.	14.38	0.30	14.26	0.43	210.04	11.54	210.83	12.10	1.100	0.080	1.080	0.070
20.	13.99	0.31	14.05	0.33	173.68	16.94	163.37	13.02	1.130	0.070	1.120	0.050

The intra-class correlation coefficients (ICC) for tension were 0.99 (95% CI: 0.98 to 0.99), between the results of subjects who measured; the ICCs for stiffness were 0.99 (95% CI: 0.98 to 1.00), and for the elasticity the ICCs were 0.97 (95% CI: 0.95 to 0.99). The Bland and Altman graphical test, comparing the differences of the measurements of two investigators, was also used for assessing the inter-observer repeatability (Fig. 13).

A



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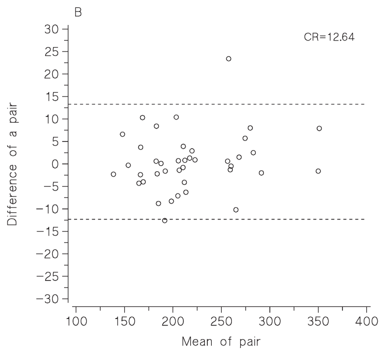

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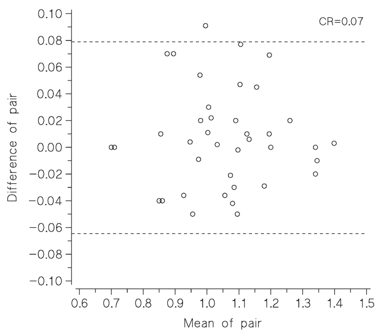

Figure 13. Bland and Altman graphical plots for repeatability of measured mechanical responses of upper trapezius muscle in relaxed sitting position with coefficients of repeatability (CR) also indicated: A) for natural oscillation frequency, B) for stiffness, and C) for the logarithmic decrement of damping, i.e., elasticity. In all three cases, the lines of 95% region, mean ± 1.96 SD (mean and SD for differences), are approximately symmetric around zero, and the points do not have any systematic pattern, thus confirming good inter-observer repeatability.

The repeatability study shows that the registered values for the trapezius muscle tension, stiffness and elasticity vary between the tested subjects, but the intra-class correlation coefficient (ICC) was near 1 for three muscular properties, showing that the variation within the subject (due to the investigator) is negligible, compared with the variation between the subjects.

5.3. The effect body positions on the mechanical characteristics of the upper trapezius muscle

In general, the results suggest significant changes in the measured parameters between different positions. For the overall group, tension, stiffness and elasticity do not exhibit significant changes between standing and sitting positions; individually there are numerous differences with no prevailing direction.

Lying down altered significantly the state of the muscles measured. The results were combined for each position, and a normal distribution of the values was shown. The Student's t-test was used. The box-and-whisker plot graph used for it is easily interpreted. The data gathered from each side was analyzed separately. The results are given in Mean±SD if not noted otherwise. 15 subjects (n=15) were measured from both sides of the body (Fig. 14).

For stiffness the results were as follows: On the right side of the body: 242±33.2 N/m in sitting position; 195±21.2 N/m (Mean±SD) lying supine; $t=7.49$, $P<0.0001$. On the left side of the body: 239±27.4 N/m and 179±13.1 N/m respectively; $t=9.50$, $P<0.0001$.

The values for the tension of the upper trapezius muscle decreased on the right side from sitting 13.1±1.1 Hz to lying position 10.8±0.6 Hz; $t = 6.37$, $P<0.0001$ and on the left side from 12.9±1.1 Hz to 10.1±0.8 Hz, respectively; $t = 13.79$, $P<0.0001$.

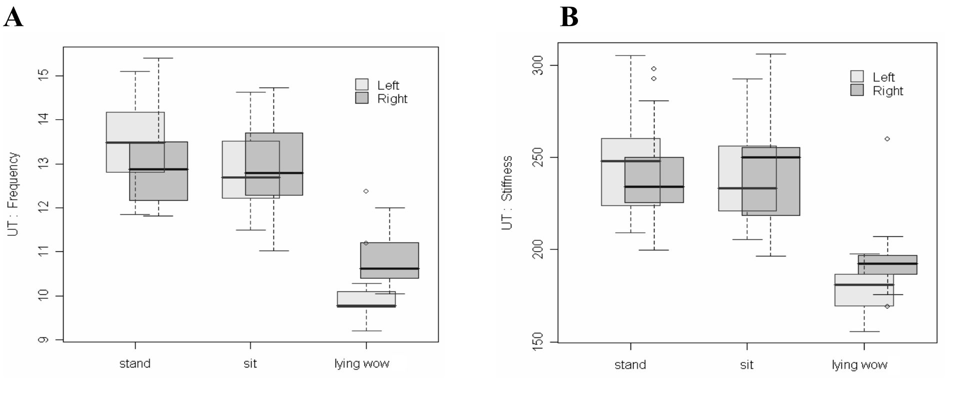

Figure 14. The box-and-whisker plot graphs for upper trapezius (UT) muscle A) tension as oscillation frequency and B) stiffness in standing (stand), sitting (sit) and lying (lying wow i.e. without water) positions, n=15.

Between standing and sitting positions there was no difference in tension, stiffness and elasticity. In lying versus standing or sitting there was clear decrease in tension and stiffness. No significant change (left: $t = -0.37$, $P=0.714$; right: $t = -1.59$, $P=0.135$; two-sided tests) appeared in the elasticity of the upper trapezius muscle.

5.4. Effect of partial head-out water immersion on the mechanical characteristics of the upper trapezius and anterior tibial muscles

To assess the effect of partial water immersion on the mechanical characteristics of resting UT and TA muscles the measurements were made, and compared, when the subject was lying supine in dry or immersed conditions (Figs. 9, 15, 16 and 17; Paper IV).

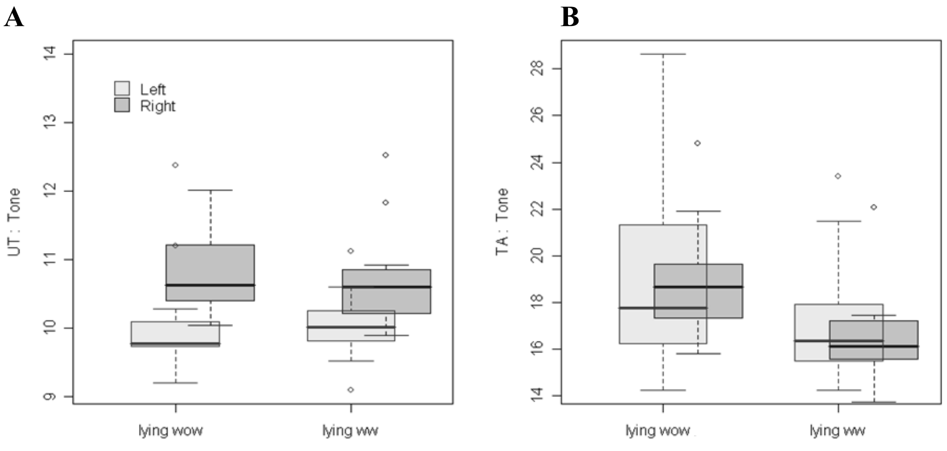

Figure 15. The box-and-whisker plot graphs for tension/tone of A) upper trapezius (UT) and B) tibialis anterior (TA) muscle in lying without water (shortly – wow) and in the water (lying ww), n=15.

For WI, the TA muscle exhibits more clear changes compared to the UT muscle in stiffness and tension. TA muscle has significantly decreasing values for both sides and for most of the individuals, 10 on the left, 14 on the right side. No significant decrease is in UT tension and stiffness.

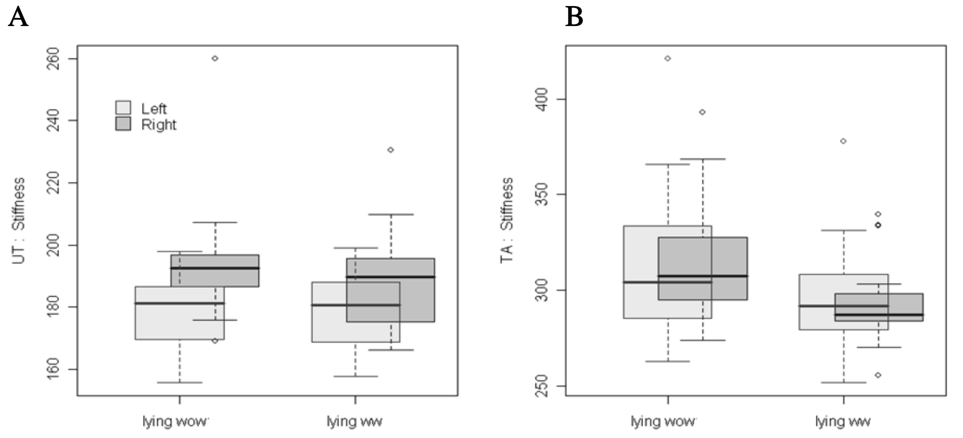

Figure 16. The box-and-whisker plot graphs for stiffness of A) upper trapezius (UT) and B) tibialis anterior (TA) muscle in lying without water (lying wow) and in the water (lying ww), n=15.

On the other hand, elasticity (reciprocal to the unitless decrement of damping, see Fig. 17) shows a significant decrease for the UT muscle, 13 on left, 14 on right side. While the (interpersonal) variance of TA elasticity is quite large, there is no significant change overall (even though individual counts show many changes).

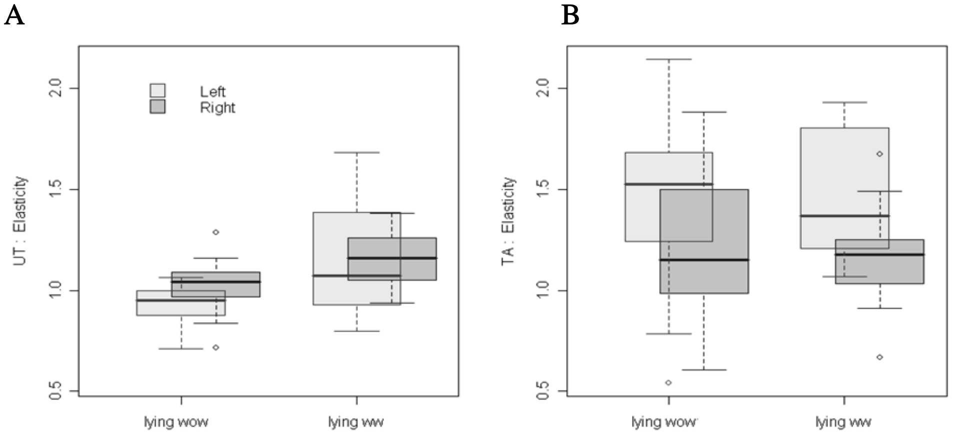

Figure 17. The box-and-whisker plot graphs for elasticity of A) upper trapezius (UT) and B) tibialis anterior (TA) muscle in lying without water (lying wow) and in the water (lying ww), n=15. Note that decrement of damping (boxes and whiskers here) characterises reciprocally property of elasticity, i.e. elasticity of UT diminishes in the water immersion.

The results seem to be robust in the sense that in the majority of cases change appears either on both or neither of the body sides. Also, individual counts seem to indicate that in many of the cases there is quite a low number of exceptional results. It seems to be plausible that a group of test subjects having similar non-myotonometric features should also have similar myotonometric parameters, especially if one looks at tension and stiffness values in lying vs. partial water immersion position for the TA muscle.

6. DISCUSSION

6.1. Relationship between intramuscular pressure and the mechanical and electromyographic characteristics of the dorsal forearm extensor and anterior tibial muscles

The findings of this study (see Paper I) confirmed that IMP and EMG almost equally estimate the relative isometric contraction force in the dorsal forearm and anterior leg (Körner et al., 1984, Parker et al., 1984 Aratow et al., 1993). While IMP is influenced by the water content, compartment volume, as well as by the properties of the surrounding muscle fascia (Bourne and Rorabeck, 1989), myotonometry better reflects tension in muscle fibres (Vain et al., 1992, Vain, 1994, 1995, 1999, Veldi et al., 2000). Muscle tension (and EMG in the dorsal forearm) showed a slightly nonlinear relationship with the relative load at 0–25% of maximal voluntary contraction. This may be caused by relatively more rapid change when the muscle was loaded with 25% MVC compared to the length at rest. Beyond 25% loading, the muscle length does not change very much.

Elasticity was not related to relative isometric contraction force, showing that this property is distinct from those mentioned above.

Correlation coefficients between IMP, EMG and myotonometry parameters revealed that muscle tension measurement and electromyography predict IMP with similar accuracy. The thickness of the subcutaneous fat above the muscle varies from subject to subject which may cause some uncertainty in the myometry measurements, though this is more significant if the fat is more than 4.0 mm thick (Boiko, 1997). Bipolar quantitative surface EMG measurements can also be influenced by many factors, like the placement of the electrodes. Such influences were minimised by normalizing all the extracted parameters to 25% MVC.

There are some earlier studies focusing on IMP and EMG during sustained contraction (Sadomoto et al., 1983, Körner et al., 1984, Sjøgaard et al., 1986, Krogh-Lund and Jorgensen, 1991, 1992, Crenshaw et al., 1997). Crenshaw et al., demonstrated that, at a 25% MVC level sustained isometric contraction IMP and EMG correlated positively. At a 70% MVC level eight out of eleven subjects showed positive correlation between IMP and EMG amplitude. Based on the mean values of all subjects, IMP and EMG amplitude increased with time during sustained isometric loading (Crenshaw et al., 1997) are some earlier studies focusing on IMP and EMG during sustained contraction (Sadomoto et al., 1983, Körner et al., 1984, Sjøgaard et al., 1986, Krogh-Lund and Jorgensen, 1991, 1992, Crenshaw et al., 1997).

In the present study an exponential fit was done to each IMP vs. time and EMG amplitude vs. time datum, and the amplitudes were correlated. In 24 out of 38 cases the EMG amplitude decreased whereas IMP decreased in 25 out of

38 subjects. Compared to Crenshaw et al. (1997), this suggests a different time-dependent behaviour of IMP and EMG amplitudes during isometric loading. In Crenshaw's study the contraction lasted until the muscle fatigued, whereas in the present study contraction was systematically measured for one minute. The increase of capillary perfusion within a muscle compartment during isometric loading probably increases intra-compartment volume by increased transudation of fluid so that the IMP rises.

In the present study, however, IMP more often decreased during prolonged loading. The time dependent behaviour of IMP might be explained by the dynamic balance of interstitial muscle fluid and the mechanical properties of the muscle and fascia. When the loading starts, the interstitial muscle pressure immediately increases. Upon increased pressure the fascia is set under tension and extended at a rate controlled by the viscoelastic properties of the tissue. All this increases the compartment volume and can reduce IMP. Finally, static mechanical equilibrium is obtained between the existing forces from the fluid flow induced muscle swelling and the tension of the fascia. Consequently, no further change in IMP will take place.

Over a wide range of submaximal contractions (10–70%) a typical increase in EMG amplitude during loading has been reported (Krogh-Lund and Jorgensen, 1991, 1992). In this study, however, the amplitude more often decreased than increased during isometrical loading EMG. This implies that motor unit activity decreases during sustained isometric contraction. In the dorsal forearm EMG amplitude showed minimal changes during sustained loading whereas IMP changed more significantly. This behaviour in the dorsal forearm is not the same as it is in the anterior leg where higher changes in both IMP and EMG amplitude can be explained by the difference in muscle geometry.

For technical reasons this study was not able to successfully conduct all EMG and myotonometric measurements but had to omit some from the final analyses (due to motion artefacts from the interface between the detection surface of the EMG electrode and the skin, and some myotonometric measurements were disturbed when muscular tremor accompanied maximal and submaximal voluntary contraction during long term recordings). The IMP-based diagnosis of chronic compartment syndrome follows the standard clinical protocol established at the Kuopio University Hospital (Jurvelin and Mussalo, 2003). Because some of the measurements were technically unsuccessful, and could not be repeated due to time limits, there is a different number of patients in the IMP, EMG and myotonometry groups, and a different number of EMG measurements during the second 100% MVC and during the long-term measurements. The different number of subjects may slightly affect the mean values of the measured parameters, but not the correlation analyses. Due to practical limitations, the consistency of the relationships between the EMG, myotonometry and IMP could not be determined. However, the mean differences in the recorded parameters during the first and last 100% MVC were close to zero indicating no systematic differences between the repeated measurements.

Another thing was that the measuring point for the Myoton tip was located between EMG electrodes taped to the skin and this may affect the result by not allowing the skin to oscillate freely. However, as the measurements were made similarly both in relaxed and contracted state, this factor did not hamper finding the differences between the states of the muscle.

With all data relative to 25% MVC load levels muscle tension characteristics were systematically higher in subjects with pathologically heightened values of IMP than in subjects with low IMP values. This finding indicates that high muscle tension might be indicative of chronic compartment syndrome. Myotonometry can therefore be a helpful tool in the diagnosis of muscle pathology.

6.2. Repeatability of the myotonometrical method in characterization of the mechanical characteristics of the upper trapezius muscle

The repeatability study (Paper II) demonstrates for the first time the simultaneous quantification of three biomechanical characteristics of the relaxed trapezius muscle in a seated person – muscle tension (as natural oscillation frequency in Hz), stiffness (N/m) and elasticity (unitless characteristic of logarithmic decrement of damping).

The Myoton device differs in principle from other myotonometers which register only stiffness of the tissue (Fischer. 1987, Bendtsen et al., 1994, Horikawa, 2001, Fukashiro et al., 2001, 2002, Leonard et al., 2003, 2004, Kato et al., 2004, Arokoski et al., 2005, Kinoshita et al., 2006). Because of its design, therefore, the Myoton is very useful.

The traditional quick release method (Pertuzon and Bouisset, 1967), the resonant frequency method (Walsh, 1992, Masi and Walsh, 2003), and the new magnetic resonance elastography (Jenkyn et al., 2001) for measuring stiffness and elasticity all require prior contraction, stretching, rotation, or vibration of the muscle being examined. These prerequisites bias the mechanical properties of muscle tissue (Hagbarth, 1994, Nordin and Hagbarth, 1996, Hagbarth and Nordin, 1998) and exclude the possibility of measuring the tension of muscles in an initial relaxed state. The mechanical energy used in a procedure by the Myoton is too small to leave any residual deformation of the tissue under investigation.

The present study demonstrates that in a mixed group of twenty women, some healthy and some with moderate musculoskeletal disorders, the tension, stiffness and elasticity of the relaxed upper trapezius muscle varies widely between its members.

The results of both investigators conform closely, which bodes well for the future application of this method. The Myoton device is reliable in the field of musculoskeletal physiology in cases where higher or lower levels of muscle tension, stiffness or elasticity might be anticipated. However, the myometric method cannot be used to investigate deep-seated muscles as they can’t be palpated.

Integration with magnetic resonance elastography (Jenkyn et al., 2001), the resonant frequency method, whole-body stiffness measurement (Smeathers and Wearing, 2001), and the other methods, will be needed to assess and interpret nano-mechanically measured stiffness and elasticity at the musculoskeletal level. Answers to questions about how the muscular system biophysically and biomechanically maintains its properties, such as elasticity, will be crucial in the fields of prevention, rehabilitation, ergonomics and gravitational physiology. Interesting pilot results of post-surgery rehabilitation have come from the field of hand surgery. Myotonometrically surveyed characteristics of relevant muscle elasticity may be helpful to warn of training too much and to ensure the quality of the postoperative treatment after tendon transfers (Lamberg et al., 2007).

Two cautions: the substrate actually measured by the Myoton includes the skin and subcutaneous tissue plus anything else between its test-end and the actual muscle, and aspects of the underlying tissue – such as the diameter of the muscle belly, and the condition of the bones and tendons supporting the muscle – also play a role in muscular oscillation. These aspects are yet to be studied.

While elaborating the design of this study, we measured the mechanical properties in 8 upper trapezius muscles by Myoton-2 myotonometry at 5 points located in the sagittal line away from and below the middle ridge of the muscle belly (see Fig. 18).

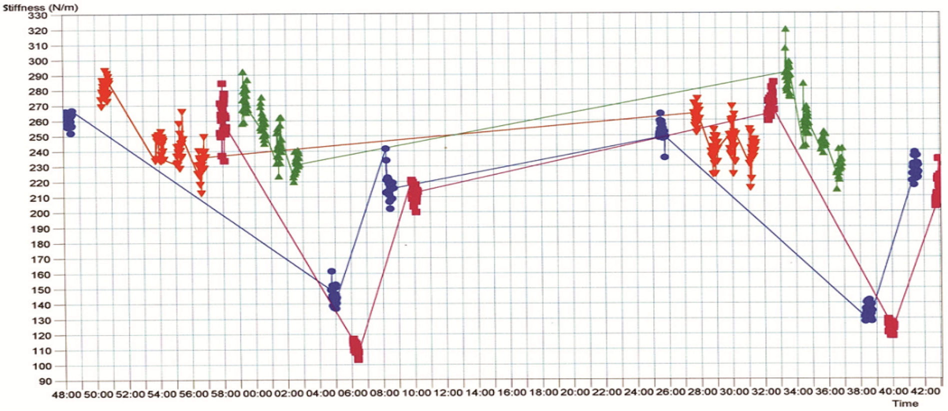

Figure 18. One male subject's raw stiffness data 1) measured from the standardized points in both left (dark blue dots) and right (plum quartiles) UT relaxed muscles in a sitting-supine-sitting protocol, and 2) measured from 5 highlighted points in a sagittal line (red triangle left and green right) away from and below the middle ridge of the UT muscle belly in only a sitting position. Both measuring protocols were done by investigators 1 and 2. Note in protocol 1 a significance decrease in the stiffnesses measured in lying supine vs. sitting position (from the approximate level of 270 N/m to 130 N/m) and not reaching the previous level of stiffness (approximately 215 N/m) when resuming the sitting position. Note in protocol 2 the nearly linear decrease in stiffness measured when moving from point to point along the sagittal line. Note also the apparent similarity between corresponding measurements of the two investigators.

The detected frequency of oscillation (tension) increased approximately 8% over each 3 mm interval in two female subjects, and over each 5 mm interval in two male subjects, along the line and starting from the highest point. This observation seems to be in line with the fibre architecture of the upper trapezius muscle (Johnson et al., 1994), and with the large variety of stiffnesses, such as titin-based ones (Neagoe et al., 2003).

Recent studies reveal the functional complexity of different tissues in the musculoskeletal system. Muscular force may be transmitted through myotendinous and myofascial systems. The latter, e.g. thoracolumbar fasciae involve contractile elements (Shleip et al., 2007). The structural compartments in thoracolumbar fasciae may be similar to those in the dorsal arm and anterior leg. Such compartments may be characterized by measuring IMP or by myotonometry. More recent studies we've done show that the patellar tendon and ligament can also be characterized using the Myoton (Viir et al., 2009a, 2009b).

6.3. The effect of different body positions on the mechanical characteristics of the upper trapezius muscle

In the present study (Paper III) myotonometrically measurable differences have been found in the mechanical characteristics of the upper trapezius muscle in sitting versus lying back positions. It is odd that there has been no attention paid to the obvious difference of the muscle tension under the force of gravity between the sitting and the lying down positions. There has been no prior direct measurement of this difference.

It should be important because seated immobility is a growing problem in all developed countries. As measured by accelerometer in the USA, adults spent approximately 8.5 h each day seated, people older than 70 years spent 9.3 h seated, but even children (6–11yrs) spent 6.1 and adolescents (16–19yrs) spent 8 hours a day seated (Matthews et al., 2008). Similar daily behaviour was found among Australian adults (Healy et al., 2007) and among British white, black and Asian adolescents (Brodersen et al., 2007). In Finland, a questionnaire showed that 46% of women and 51% of men are sitting for at least 6 h every day (Sjöström et al., 2006).

The upper trapezius muscle is often used as representative of the neck and shoulder girdle to clarify the sources of musculoskeletal disorders of the upper spine region. There are epidemiological studies supporting the so called Cinderella hypothesis (Hägg, 1991), that a low rate of short interruptions in electrical activity (EMG caps) is behind the development of complaints (Veiersted et al., 1990), but this relationship was not found in office workers with NS pain (Vasseljen et al., 1995). It was not confirmed that so called Cinderella fibres becoming overloaded with low level electrical activity, and becoming metabolically exhausted (Sjogaard and Jensen, 1999), are the reason of the disorders of the neck and shoulder area. As SEMG studies were unable to reveal quantitative EMG indicators and functional tests that could objectively assess disorders in neck and shoulder girdle (Sjøgaard et al., 2006), the reason must be elsewhere. In the present study the change in posture brought out measurable mechanical differences.

The incapacity to correlate and integrate the mechanical characteristics of muscles with motor control effects and the role of different levels of the electromyographically assessable muscle activity is a limitation in this study. In whatever way one describes the steady-state muscle tension (which maintains the sitting position) – the voluntary or nonvoluntary contraction, or also the so-called unnecessary component of tension, all analyzed by Simons and Mense (1998) – the fact is that reclining to a horizontal position gives a prompt, measurable decrease in this tension.

The differences were evident in all participants, and, in most cases, changes in tension and stiffness were significant on both sides. Changes in elasticity were not so prominent. This highlights the fact that there is significant personal variability in this particular aspect and that these three properties act separately from each other.

Caution in this study is related to subject positioning. A mechanical impulse to provoke oscillation in UT muscle was given in sitting position 3 mm and in lying position 5 mm below the middle ridge, to keep the testing end of device in the same radius to muscle belly direction and at a 15º vertical angle relative to the direction of the force of gravity. The work-principle of the Myoton device is gravity sensitive but the effect of this on recorded values was not tested. However, the decrease in tension and stiffness when lying back is obvious (see example of raw stiffness data, Fig. 18) as at each point records in sitting are at an approximately double the level than when in the supine position (280–230 N/m vs. 145–110 N/m).

Neck, shoulder, and low back pain are related to persistent sitting both in young people (Auvinen et al., 2007, Auvinen et al., 2008), and in the employed elderly (Hartvigsen et al., 2000, Lis et al., 2007, Coté et al., 2008). A kyphotic sitting posture seems to develop more severe changes in the spine (Pynt et al., 2008). Women over 65 years, who spend a long time sitting, have a higher risk of hip fracture than those who spend less time in that position (Gregg et al., 1998).

"Epidemic seated immobility" is frequently a root cause for the epidemic of obesity among young, adult and elderly people (Tucker and Friedman, 1989, Tucker and Bagwell, 1991, Prentice and Jebb, 1995, Ching et al., 1996, Hill et al., 2003, Hu et al., 2003, Mummery et al., 2005, Must and Tybor, 2005, Must et al., 2007, Vuori and Laukkanen, 2009, Thorp et al., 2010). High blood pressure, increasing waist girth, and the metabolic syndrome are all related to seated immobility in adults and children (Bertais et al., 2005, Ford et al., 2005, Dunstan et al., 2005, Ekelund et al., 2006, Andersen et al., 2006, Levine, 2007, Healy et al., 2008a, Sardinha et al., 2008, Healy et al., 2008b).

Extremely important is the fact that the relationship between seated immobility and the above mentioned health problems is shown to be independent of physical activity (Hamilton et al., 2007). Therefore, the scientific community has a new task – the study of the physiology of inactivity (Owen et al., 2009, Bak et al., 2010). Seated immobility is one of the most important challenges in dealing with modern chronic diseases. Primary prevention is our task (Booth et al., 2000, Booth et al., 2002, Naylor and McKay, 2009, Viir, 2010). Exercising in leisure time does not counteract the effect of constant sitting. Enhanced understanding of the biomechanics of being seated is urgently needed.

A key approach in the present study in respect of this common phenomenon has been using body position as the only variable. The finding that changing from a sitting to a supine position reduces the muscle tension and stiffness by up to one fifth has not been described numerically before and thus is novel. This is confirmed by a recent study demonstrating that lying back gives prompt decrease of UT muscle tension and stiffness also in fibromyalgia patients (Viir et al., 2008a).

Up to 40% of human body weight consists of muscle tissue. Understanding the functional role of this tissue is the main topic of exercise biology and indeed the key approach to preventing related disorders. Much attention has been given to the muscle system to find out how to achieve better endurance, an explosive start or more strength. Better performance is achieved with muscle tissue contractile activity in different time, velocity and loading patterns. The most important loading factor, to which all muscle and other tissues are particularly adapted, is an environmental factor – the force of gravity. The immediate decrease in the tension and stiffness of the upper trapezius muscle, which occurs with a change from a sitting position to a supine position, clearly demonstrates that the sitting position requires greater tension and stiffness to maintain. One can speculate that this might be true for the overall musculature.

Proper appreciation of this simple phenomenon may lead to new ways of treating and preventing neck and shoulder disorders in sedentary people (Viir et al., 2008a, 2008b). The pathophysiology for the majority of neck pain conditions is not clear. There is evidence for disturbed oxidative metabolism and elevated levels of pain-generating substances in neck muscles, suggesting that impaired local muscle circulation or metabolism could be part of the pathophysiology (Larsson et al., 1993, Visser and van Dieën, 2006). It seems plausible to suppose that many gentle unchallenged movements performed in the supine position may result in different effects with respect to micro and macro circulation, as compared with those done in semi- or upright positions. For instance, it is already known that flexing the feet while lying down more than doubles the lymph flow, as compared with the rate of flow achieved when exercising in other, upright positions (Olszewski and Engeset, 1980, Engeset et al., 1997). In addition, the fact that stiffness decreases when a person lies down may mean that the circulation of blood and lymph in the body is also similarly enhanced when the gravitational load is decreased. It is hypothesized that in the microgravity condition the driving force for the fluid shift is the intrinsic and unopposed lower limb elasticity that forces venous blood and then other fluid in the cranial direction (Thornton et al., 1974). In gravitational physiology, the so-called two hearts model is used to describe the pumping cooperation between heart and musculature (Rowell 1993, Casey and Hart 2008, Panny et al., 2009, Nådland et al. 2009). The heart circulates 5–6 litres of blood, but approximately 2/3 of the body is water-based liquids; surely the heart cannot circulate this amount alone.

Gravity influences living systems. Gravitational biology has confirmed the direct action of gravity at the cellular and organism level that requires hierarchical structural support functioning to operate normally in 1 G on Earth (Yamashita and Baba, 2004). Gravity feels like a force you can trust. Every day, unwaveringly, it keeps your feet planted firmly on the ground (Hogan, 2007). Weightlessness, during a Space mission, doesn't need the support function so muscular tension and stiffness diminish. Sitting, on the other hand, constantly overuses the positional control function of our muscles. Despite huge differences, both in physiological impact and physical distance, some similarities may be found between these two conditions.

In Space where there is no force of gravity there is no walking and so no rhythmic mechanical stimulation of the feet and no longitudinal stimulation of the muscles and connective tissue of the body as a whole. These stimulations are also absent during seated immobility. In Space the muscles of the feet are protected from atrophy by simulating their normal function with special boots. These boots have insoles driven by pneumatic pumps to mimic slow or fast walking or running by applying respective rhythmic pressure of up to 200 g/cm² to the sole of the foot (Layne et al., 1998, Miller et al., 2004, Forth and Layne 2008).

Both during weightlessness (Space) and during sitting, the inactive lower extremity muscles diminish their support for the cardiovascular function, and all skeletal muscles.

The strongest association of neck and shoulder symptoms is with the duration of computer work in a sitting position without breaks (Karlqvist et al., 2002). It has been shown that more frequent regular breaks from persistent sitting diminish metabolic syndrome risks (Healy et al., 2008c). In EU directives those working in a sitting position are advised to take regular breaks.

It is my hypothesis (though not yet proven) that hourly two minute breaks from sitting, spent lying and making gentle rhythmic movements with the legs simulating walking, alternated with relaxed simple rotations of the shoulders and arms, could ameliorate the effect of prolonged sitting and restore the viability of muscles, keeping them in good tonus throughout the working day.

This hypothesis is in line with a study exploring whether the work-time recovery of the spinal condition of aircraft loaders could be improved by spending the pauses supine as against in a conventional sitting position. The effects of loading and recovery on the spine were measured as changes in body height. The increased gain of body height during pauses spent supine was seen as an indication of increased fluid flow into and out of the IV discs during pauses and handling work, respectively.

Leisure activities which would allow lying during breaks increase disc height changes and their fluid exchange, and thus even a few minutes of lying might be beneficial, Leskinen et al. concluded in 1991 (see also Figure 19 for a note about similarity in principle between the approaches of Leskinen et al. and myself).

6.4. The effect of partial immersion on the mechanical characteristics of the upper trapezius and anterior tibial muscles

The present non-invasive study (Paper IV) describes how the tension and mechanical properties of skeletal muscle are affected by the positioning of the human body relative to the force of gravity (in standing, sitting and lying positions and in partial WI condition), using an instrument that has only recently become available. Skeletal muscle in action, for example related to speed of locomotion or strengthening, can be easily assessed as we can change the speed of a treadmill or the torque in a strength machine. Changing the variable relevant to the support function (the force of gravity) is impossible on the Earth's surface. Changing the effect of gravity, very significant to the support function, is easier. Microgravity simulation models like Bed Rest and WI have been widely used for determining the effects of gravity (Shulzhenko and Vil-Viliams, 1976, Desplanches, 1997, di Prampero and Narici, 2003, Rittweger et al., 2005, Pavy-Le Traon et al., 2007, and many others).

Interestingly, the state of intervertebral discs has been studied invasively in these three positions by the "Dr. Spine of the World" – Alf Nachemson – with James Morris (1964), and Dr. Martha Kurutz (2006) have examined intervertebral disc behaviour in water immersion with ultrasound monitoring. The results of these three studies together show the integrated cooperation of the human musculoskeletal system under the force of gravity (Fig. 19).

In the present study there is a clear and distinct decrease in tension and stiffness of UT muscle going from upright standing and semi-upright sitting posture to lying (as in BR), reflecting the change in the direction of the gravitational force relative to the body. The elasticity of the muscle also seems to be affected by the change in posture, but it is difficult to explain the nature of the change. Further studies are needed to pursue this, especially as the disproportion between stiffness and elasticity of muscle tissue as it alternates between contraction and relaxation has been proposed as a new marker of the functional state and of possible pathological changes in muscle tissue (Veldi et al., 2000).

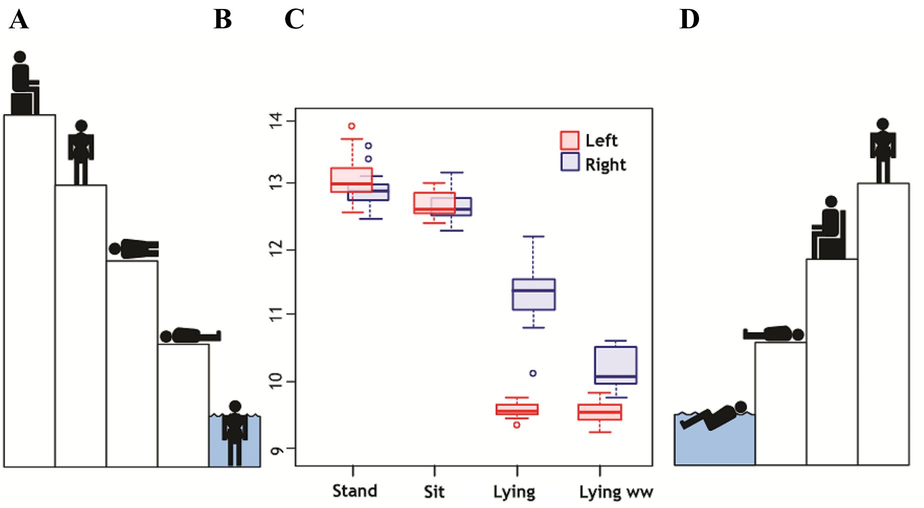

Figure 19. A combined representation for three integrated studies: A) adopted from a classical study of intravertebral disc pressure by Nachemson and Morris, B) intravertebral disc heightening in water immersion study by Kurutz et al. 2006, using ultrasound, C) upper trapezius muscle tension in standing (Stand)-sitting (Sit)-lying-PHOWI (Lying ww, i.e. within water) protocols, and D) illustration of present study results in principle.

PHOWI seems to further influence the characteristics of the muscles, with a clearer effect on the TA muscle tension and stiffness. The results for the UT muscle are not as clear in PHOWI, perhaps being related to a previous finding that neck muscle volumes do not change during spaceflight, which was considered surprising at the time (LeBlanc et al., 2000). Perhaps the level of water in PHOWI was such that the subject floated slightly even though we tried to avoid this. If this were so, the UT muscle would have become active in trying to hold the position of the body. In most cases elasticity appears to be erratic and this is difficult to understand. Indeed PHOWI reduced the weight of not only the UT and TA but of all other muscles below water level.

Further, as the UT and TA muscles were only partly submerged in this study, it is interesting to speculate that changes in muscle tension, stiffness and elasticity in directly measured UT and TA muscles reflect the state of the tensed network of the overall muscular system. This question remains to be explored in further studies of different design, which would include lying prone and the assessment of spinal muscles.

Distinguishing between skeletal muscles affected by gravity and those that are not is an approach used also in occupational, preventive and rehabilitative medicine. But it may not be the best choice. Naturally, in the so-called postural muscles, support is the primary function, but it is naïve to think that the so-called tonic muscles like TA have no role against the force of gravity. The significant decrease of tension and stiffness of TA in PHOWI found by this study is relevant to the recommendation of di Prampero and Narici (2003) that studies should be done of how the tonic as well the so-called postural muscles support the body.

The Myoton uses myotonometric technology to measure the tension, stiffness and elasticity of muscle. It has proved to be a simple and reliable tool during this study, and the results appear consistent and credible. The device is easy to handle physically; experience, good understanding of human anatomy, concentration, knowledge of standardization requirements (measuring point, angle of body posture, etc.) are nevertheless, as in all experiments, prerequisites for reliable results.

As muscles seem to be more relaxed when lying and when immersed in water, it is interesting to see how exercising under these conditions affects the outcome, especially where movement in standing or sitting positions causes pain, as in several medical disorders. We agree with Epstein (1992): "In view of this long history, it is ironic that the recent widespread interest in water immersion as an investigative and therapeutic tool received its impetus not from centuries of hydrotherapeutic practice but from the modern space program". Water immersion therapy is regaining its significance in the therapy of musculoskeletal, cardiovascular, nephrogenic and other disorders and in ailments related to ageing (Ahlqvist, 2002, Kargülle and Donmez, 2002, van Tubergen and Hidding, 2002, Mannerkorpi and Iversen, 2003, Pechter et al., 2003a, 2003b, Mannerkorpi, 2005, Bender et al., 2005, Bilberg et al., 2005, Codish et al., 2005, Gusi et al., 2006, Perret et al., 2006, Tomas-Carus et al., 2007, Balint et al., 2007, Munguia-Izquierdo and Legaz-Arrese, 2008, Tomas-Carus et al., 2008, Barbosa et al., 2009).

There are many studies that describe broadly and variously the effects of exercising in WI (Davis and Cavanagh 1993, Poyhonen et al., 2002, Alkner et al., 2003, Pendergast et al., 2003, Reilly et al., 2003, Broman et al., 2006, Masumoto et al., 2007, Yavus et al., 2007). Some of these are related to Space Life studies but none of them explicitly declares the dramatic diminishing of the gravitational loading to be most important recovery factor of aquatic therapy. Many previous studies have aimed to increase athletic or general performance. They have largely overlooked the possibility that simply walking when immersed up to the neck may cause greatly heightened sensory input from the rhythmic mechanical pressure at the forefoot and heel while at same time eliminating the effect of body weight on dysfunctional joints, which can be very significant for rheumatic patients and obese people.

WI treatment of musculoskeletal disorders may well be as effective as the use of stimulation of foot support zones imitating natural rhythmic locomotion (Netreba et al., 2004, Kozlovskaya et al., 2007, Forth and Layne 2008), which, in the early period of recovery have been shown to cancel out tibialis anterior vs. soleus muscles tension asymmetry in resting patients with ischemic stroke (Miller et al., 2005). The study of these possibilities would be one of the objectives of future projects, and would give the opportunity to incorporate the findings of Space Life Science into rehabilitation and prevention therapies.

The feeling of relative weightlessness may also serve as a good motivator for patients undertaking aqua therapy. It is essential that individuals are self-motivated to lead a healthy life. Whatever decisions are taken by officials or doctors to improve the wellbeing of those who suffer from musculoskeletal disorders, or ultimately to prevent them, the motivation to benefit from those decisions must be found by patients themselves. For pool exercising, it is useful for the individuals to know about the influence of WI. For example, WI from the neck down for 30 minutes decreases the pressure on spinal discs so that a person can gain up to two centimetres in body length (Kurutz, 2006). This is similar to the change in body length in everyday life between standing or sitting during the day and lying and sleeping at night.

There seems to be a clear tendency for the tension and stiffness of the UT muscle to decrease when going from a sitting to a lying position. The effect of partial WI is significant and more substantial on the TA than on the UT muscle, showing relaxation (lower values of stiffness and tension) as well as change in elasticity. Our results are in line with classic weightlessness studies showing a strong correlation between the decrease in skeletal muscle tension and the various degrees of support reduction under WI and BR (Kozlova and Ilyina, 1984, Gazenko et al., 1987, Timanin 1989, Gallasch and Kozlovskaya, 1998, Kozlovskaya, 2002, Kozlovskaya et al., 2007). Our results and approach may also give insights for better understanding of the effects on the muscles of seated immobility and of variation in support function loading.

In principle, significant change in skeletal muscle under full weightlessness or ground-based microgravity could be considered one of the most easily understandable effects. The single most significant environmental change for the human body is any substantial change in the force of gravity. Its elimination or reduction quickly alters the contribution of the muscular system to bodily support. Understanding the responses of the normal biological systems to microgravity, as well as elucidation of the basic mechanisms by which these effects occur, may help considerably in developing strategies to overcome the plethora of biological disorders associated with extremely sedentary lifestyles (Edgerton and Roy, 2000, Heppener et al., 2008, Navasiolava et al., 2010, Vernikos and Schneider, 2010).

The present experimental study gives for the first time a mechanical characterization of skeletal muscle tension, stiffness, and elasticity, for people in different positions, and in water immersion. The results suggest how the global challenge of seated immobility might be faced, and how working strategies for prevention and rehabilitation of the musculoskeletal system may be developed. Indeed, muscular wellbeing is the basis for overall health.

CONCLUSIONS

1. For the tibialis anterior muscle, strong positive correlations were established between both tension and electromyographic activity with intramuscular pressure, whereas for the forearm extensor muscle moderately positive correlations were found between these characteristics.
2. Myotonometrically registered mechanical characteristics vary between the tested subjects and were individual-specific. The high intra-class correlation coefficient shows that the variation in measurements, conducted by the two investigators, is negligible. The myotonometry method is reliable for describing the mechanical properties of skeletal muscle.
3. There were no significant differences in upper trapezius muscle mechanical characteristics between standing and sitting positions. Changing from standing and sitting positions to supine position reduced the tension by up to 20% in the upper trapezius muscle.
4. The partial head-out-of-water immersion diminished muscle tension. The effect of immersion was significant and more substantial on tibialis anterior than on upper trapezius muscle.

In general passive muscle tension has been established as an important characteristic of the support function, against gravitational load, of skeletal muscles. The changes in this tension engendered by changes in bodily positions, or by partial immersion in water, have been objectively demonstrated and quantified.

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SUMMARY IN ESTONIAN

Erinevate kehaasendite ja veesoleku mõju passiivse skeletilihase mehaaniliste omaduste näitajatele

Sissejuhatus

Oma pika kliinilise praktika jooksul taastusraviarstina panin tähele, et tõsiselt haigete reumapatsientide enesetunne paranes märgatavalt, kui nad tegid neile sobivas tempos kergeid harjutusi kas basseinis või selili lamades. Ühtlasi tõdesin palpeerides, et trapetslihase toonus muutub tunduvalt, kui patsient heidab selili võrreldes sellega kas ta seisab või istub. Siit tekkis hüpotees, et need kaks nähtust peaksid olema seotud, ning ma asusin otsima võimalusi seda nähtust uurida.

Skeletilihase toonuse mõiste on esile kutsunud palju diskussioone ning üheselt ei mõisteta seda tänaseni. Skeletilihaste toonus on oluline faktor, mis hoiab keha püsti, säilitab keha olekut erinevates poosides ja tagab taustapinge aktiivsete liigutuste tarvis. Arvatakse, et lihastoonus on tagatud eelkõige mitte neuro-reflektoorsete vaid mehaaniliste mehhanismide läbi.

Palpeerimine on olnud ja on siiamaani kõige tavalisem lihastoonuse kliinilise hindamise füüsikaline meetod, aga kahjuks on säärane hindamine subjektiivne. Et paremini aru saada skeletilihaste toonust tagavatest biomehaanilistest omadustest ning nende rollist neuromuskulaarsetes ja muskuloskeletaarsetes füsioloogilistes protsessides, on tarvis neid omadusi mõõta objektiivselt. Sellisel juhul saaks jälgida häirete tekkimist, süvenemist ning taandarengut, mida oleks vaja näiteks haiguse kulu prognoosimiseks ja raviprotseduuri hindamiseks.

Siiamaani on puudunud usaldusväärne seade, millega registreerida lihase biomehaanilisi omadusi tema erinevates seisundites: kontraktsioonis või venituses, aga eriti ka lõõgastunud seisundis, kui puudub kontraktiivne aktiivsus. Selles uurimistöös on skeletilihaste toonust mõõdetud seadmega nimega Myoton, mille on välja töötanud dr Arved Vain (2000) Tartu Ülikoolis. Myoton seadme töötamise printsiibiks on aparaadi enda poolt esile kutsutud lihase sumbuva võnkumise registreerimine kiirendusanduri abil. Saadud tulemustest kalkuleerib seadme miniarvuti arvulised näitajad lihase toonusele, jäikusele ja elastsusele. Mõõtmine on mitteinvasiivne ja seade portatiivne.

Antud aparaati on mitmetes uuringutes kasutatud, eelkõige spordimeditsiini ja kehakultuuri vallas. Kontraheeruvatel lihastel tehtud korratavusuuringute ja mitmete, sealhulgas pilootuuringute põhjal on leitud, et müotonomeetriline meetod võimaldab registreerida skeletilihaste biomehaaniliste omaduste erinevust uuritud katsealuste vahel ja teatud haigusseisundite puhul, ning jälgida nende omaduste muutumist ajas.

Minu huvi on keskendunud sellele, kuidas varieerub tahtlikust pingest vaba lihase toonus, kui inimene on ühes või teises asendis – istub, seisab, on pikali –

või lamab osaliselt vees, ja hakkasin otsima viise, kuidas neid varieerumisi mõõta; seejuures avastasin oma üllatuseks, et selles vallas polnud sinnamaani mingeid mõõtmisi tehtud. See muutus võimalikuks alles tänu dr Vainu poolt välja arandatud meetodile, mille edasiarendamisel ta minu soove ja ettepanekuid lahkesti arvestas.

Uurimistöö eesmärk ja ülesanded

Uurimistöö põhiülesandeks oli selgitada kehaasendi muutuse ja veesoleku mõju lihaste toonuse näitajatele.

Konkreetsemad ülesanded olid järgmised:

1. Uurida käsivarre ekstensorlihaste ja eesmise sääreluulihase (TA) mehaaniliste, elektromüograaafiliste ja lihasesisese rõhu näitajate seoseid. (Publikatsioon I).
2. Uurida müotonomeetrilise meetodi usaldusväärsust ja korratavust trapetslihase ülaosa mehaaniliste omaduste määramisel (Publikatsioon II).
3. Võrrelda trapetslihase ülaosa mehaanilisi omadusi lamades-, istuvas ja seisvas asendis (Publikatsioon III).
4. Hinnata osalise veesoleku (PHOWI) mõju trapetslihase ülaosa ja eesmise sääreluulihase mehaanilistele omadustele (Publikatsioon IV).

Uuritavad ja kasutatav metoodika

Uuringud olid kooskõlastatud Päijät-Häme tervishoiupiirkonna eetikakomiteega (*Ethical Committee of the Päijät-Häme Hospital District*) ja Tartu Ülikooli Inimuuringute Eetika Komiteega.

Esimene uuring viidi läbi Kuopio ülikooli haiglas (*Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital and University of Kuopio*). Kõik 37 osalejat kannatasid valude all kas käsivarre sirutajalihaste piirkonnas või eesmise sääreluulihase piirkonnas. Patsiendid olid uuringu ajal selililamangus. Küünarvarre lihaseid ja eesmist sääreluulihast koormati labakäe ja labajala dorsioflektsioonis isomeetriliste kontraktsioonidega. Koormust jälgiti dünamomeetriga ja see oli doseeritud lähtuvalt eelnevalt registreeritud maksimaalsest kontraktsioonist. Sama-aegselt iga kontraktsiooniga registreeriti lihasesisest rõhku ning elektromüograafilisi ja müotonomeetrilisi omadusi.

Teises uuringus oli 20-st osalejatest 15 kergema astme muskuloskeletaarsete kaebustega patsiendid ja 5 üldiselt tervet haigla töötajat. Uuringu käigus mõõdeti istuvatel katsealustel kahe uuringu läbiviija poolt kordamööda sama Myoton seadmega nende trapetslihase ülaosa mõlemalt kehapoolelt.

Kolmas ja neljas uuring tehti Tartu Ülikooli Kehakultuuriteaduskonna Kinesioloogia laboratooriumis ja selles osales 15 tervet noort tööealist naist, kellede põhiline töövahend oli arvuti. Nende trapetslihase ülaosa biomehaanilised omadused määrati mõlemalt kehapoolelt seistes, istudes, selili ja olles osaliselt selili vees spetsiaalses ergonoomilises vannis. Samuti registreeriti eesmiste sääreluulihaste biomehaanilised omadused mõlemal jalal uuritavate lebades selili kuival ja seejärel spetsiaalses veemahutis.

Järeldused

1. Eesmisel sääreluulihasel esineb tugev positiivne korrelatsioon nii elektromüograafiliste kui ka mehaaniliste näitajate ning lihasesisese rõhu vahel. Trapetslihasel on see korrelatsioon keskmise tasemega.

2. Müotonomeetriliselt registreeritud lihase toonuse, jäikuse ja elastsuse väärtused varieeruvad oluliselt mõõdetavatel indiviididel ja on seega individuaalsed. Erinevate uurijate vaheline kõrge korrelatsioonikoefitsient (ligikaudu 1) näitab meetodi head korratavust.

3. Müotonomeetrilise seadmega Myoton mõõtes ei ole olulist erinevust trapetslihase ülaosa mehaanilistes omadustes vaatlusalustel seistes ja istudes. Seejuures lamavas asendis väheneb trapetslihase ülaosa toonus ja jäikus oluliselt (kuni 20%).

4. Osaliselt vees viibimine alandab lihastoonust, seejuures veekeskkonna mõju eesmisele sääreluulihasele on statistiliselt oluline ja enam väljendunud kui trapetslihase ülaosale.

Kokkuvõtteks: passiivne lihaspinge on gravitatsiooni mõjuväljas toimivate skeletilihaste toefunktsiooni oluline karakteristik. Kehaasendite ja osaliselt veesoleku poolt esile kutsutud lihaspinge muutused on uuringus objektiivselt ja kvantitatiivselt esitatud.

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Education

1961	Tartu 2 Secondary School;
1961–1968	Faculty of Medicine, University of Tartu;
1966	Instructor of Folk Dances from University of Tartu
1968	MD, graduated from University of Tartu
1973	Physiatrist / Physical and Rehabilitation Medicine from University of Tartu
2008–2010	PhD-study (Exercise and Sport Sciences), Faculty of Exercise and Sport Sciences, University of Tartu.

Professional Employment

2001–2010	Contract physician and researcher in Centre of Rehabilitation, Rheumatism Foundation Hospital, Heinola
1987–Present	Private physician
1982–1987	Physician at Kiljava Hospital, Kellokoski Hospital, Heinola Rheumatism Foundation Hospital and Helsinki Deaconess Hospital
1981–1981	Junior researcher, Institute of General and Molecular Pathology University of Tartu
1981–1981	Physician, Tartu Oncology Clinic
1977–1980	Chief Doctor, Värska Innovative Balneotherapy Hospital
1969–1977	Chief Doctor, Värska Hospital
1968–1969	Ship doctor at Tallinn Seamen's Hospital/fishing base ships Stanislaw Monjuschko and Frederick Chopin
1963–1964	Nurse, Trauma Station, Tartu University Hospital

Specialized Courses

- Advanced Intensive Course on "Interaction between Nervous Control and Musculoskeletal loading in Normal and Abnormal Locomotion and Training", organized by Neuromuscular research Centre Department of Biology of Physical Activity University of Jyväskylä, Finland 29th November–1st December 2007
- The International 19th Puijo Symposium: Physical Activity, Muscle Metabolism and Insulin Resistance, June 27–29. 2007, Finland
- LBP, Controversies in Clinical Practice and Research, 8th Physiatric Summer School Society for Back Pain Research, Rehabilitation ORTON, Invalid Foundation, Helsinki, Finland 27th to 29th of June, 2007
- 57th IAC, International Astronautical Congress, Valencia, Spain, October 02–06, 2006
- Masterclass in Ancylosing Spondylitis, University of Helsinki / Rheumatism Foundation Hospital Heinola, 09.02.2006, Helsinki
- The 6th Head-Out Water Symposium: From Bathing to Space, Sept. 21–22, 2005, Nagoya, Japan
- International Research Seminar, The European Regional Developmental Fund Southern Finland Coastal Zone Interreg IIIA programme, The Rheumatism Foundation Hospital Heinola, Finland November 22–26, 2004
- Cervico-Cranio-Mandibular Disorders, 5th Physiatric Summer School Rehabilitation ORTON, Invalid Foundation, Helsinki 19–20 August, 2004
- The First Symposium on Cryotherapy at Rheumatism Foundation Hospital Heinola, Finland 17.–18.10.2003
- Low Back Pain – New Perspectives and Clinical Applications, 4th Physiatric Summer School, ORTON Invalifoundation, 21–22.8.2003, Helsinki

Organising of Conferences

1991 Tomorrow's Birthday Symposium, Dipoli, member of organising committee

1992 Karl Ernst von Baer Jubilee Year Conference Health and Disease in Man, Society and Nature, Tartu, Conference Chair

1994 Yehudi Gordon, MD, FRCOQ, FCOGSA Natural Birth Workshop, Tartu, member of organising committee

2008 7th Head-Out Water Immersion Symposium: From Bathing to Space and Daily Living, Secretary General

Main Research Interests:

- Effect of rehabilitation interventions
- Musculoskeletal system function of support against gravity
- The inactivity physiology and seated immobility
- The water immersion microgravity simulation model and exercise therapy in water immersion
- The primary prevention of the musculoskeletal disorders

Membership in professional organizations:

- International Society of Biomechanics, member
- The International Institute of Informatics and Systemics (IIIS), Florida, USA, member
- International Astronautical federation, member
- Finnish Society for Rheumatology, member
- The Finnish Society of Physical and Rehabilitation Medicine, member
- Estonian Naturalists Society, member
- Finnish Society of Physicians, member
- Finnish Society of Egyptology, member

Publication Summary

The total number of scientific publications is 32, including 4 papers in international refereed journals, 2 other scientific papers and 23 conference abstracts.

ELULOOKIRJELDUS

Ragnar Viir

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Haridus

1956–1961	Tartu Miina Härma nim. II Keskkool
1961–1968	Tartu Ülikool, arstiteaduskond
1966	Rahvatantsu instruktor, Tartu Ülikool
1973	Arst-füsioterapeut, Tartu Ülikool
2008–2010	Doktorantuur Tartu Ülikooli spordibioloogia ja füsioteraapia instituudis

Erialane teenistuskäik

1963–1964	Meditsiini-õde traumapunktis, Tartu Kliiniline Haigla
1968–1969	Laeva-arst ujuvatel kalabaasidel Stanislaw Monjuschko ja Frederick Chopin
1969–1977	Värska Haigla peaarst
1977–1980	Värska Eksperimentaalse Vesi-mudaravila peaarst
1981–1981	Tartu Onkoloogiahaigla arst
1981–1981	Noorem teaduslik töötaja Üld- ja molekulaarbioloogia instituudis
1982–1987	Arst Kiljava, Kellokoski, Heinola Reumafondi ja Helsingi Diakonissa haiglates
1987–jätkub	Era-arst
2001–2010	Lepinguline arst ja teaduslik töötaja Reumafondi Haiglas, Heinola

Erialane enesetäiendus

- Advanced Intensive Course on "Interaction between Nervous Control and Musculoskeletal loading in Normal and Abnormal Locomotion and Training", organized by Neuromuscular research Centre Department of Biology of Physical Activity University of Jyväskylä, Finland 29th November–1st December 2007
- The International 19th Puijo Symposium: Physical Activity, Muscle Metabolism and Insulin Resistance, June 27–29. 2007, Finland

- LBP, Controversies in Clinical Practice and Research, 8th Physiatric Summer School Society for Back Pain Research, Rehabilitation ORTON, Invalid Foundation, Helsinki, Finland 27th to 29th of June, 2007
- 57th IAC, International Astronautical Congress, Valencia, Spain, October 02–06, 2006
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- The 6th Head-Out Water Symposium: From Bathing to Space, Sept. 21–22, 2005, Nagoya, Japan
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- Cervico-Cranio-Mandibular Disorders, 5th Physiatric Summer School Rehabilitation ORTON, Invalid Foundation, Helsinki 19–20 August, 2004
- The First Symposium on Cryotherapy at Rheumatism Foundation Hospital Heinola, Finland 17.–18.10.2003
- Low Back Pain – New Perspectives and Clinical Applications, 4th Physiatric Summer School, ORTON Invalifoundation, 21–22.8.2003, Helsinki

Erialaorganisatsioonid

- Eesti Loodusuurijate Seltsi liige
- Soome Arstideliidu liige
- Soome Reumatoloogide Seltsi liige
- Soome Füsiaatria ja Rehabilitatsiooni Ühingu liige
- Rahvusvahelise Biomehaanika Seltsi liige
- Rahvusvahelise Informaatika ja Süsteemika Instituudi (IIIS), Florida, USA, liige
- Rahvusvahelise Astronautika Föderatsiooni liige
- Soome Egiptoloogia Seltsi liige

Kongresside korraldamine

1991 Sümpoosium Homne sünnipäev, Dipoli, organiseerimiskomitee liige

1992 Karl Ernst von Baeri Juubeliaasta Konverents: Tervis ja Haigus Inimeses, Ühiskonnas ja Looduses, Konverentsi peakorraldaja

1994 Yehudi Gordoni, MD, FRCOQ, FCOGSA Loomuliku Sündimise Workshop, Tartu, organiseerimiskomitee liige

2008 7th Sümpoosium: Inimene kaalutuses ja vees (Head-Out Water Immersion Symposium: From Bathing to Space and Daily Living), peasekretär

Teadustegevus

- Rehabilitatsiooni-interventsioonide efektiivsus
- Muskuloskeletatiivse süsteemi tugifunktsioon gravitatsioonijõu vastu
- Füüsilise inaktiivsuse füsioloogia ja istumise liikumatus
- Mikrogravitatsiooni maapealse simuleerimise vesi-immersiooni mudel ja vesivõimlemine
- Muskuloskeletatiivse süsteemi primaarne preventsioon

Kokkuvõte publikatsioonidest

Kokku on ilmunud 32 teaduspublikatsiooni, milledest 4 publitseeritud rahvusvaheliselt refereeritavates ajakirjades, 2 muud teadusartiklit ja 23 teadusürituste teesi.

DISSERTATIONES KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

1. **Lennart Raudsepp.** Physical activity, somatic characteristics, fitness and motor skill development in prepubertal children. Tartu, 1996, 138 p.
2. **Vello Hein.** Joint mobility in trunk forward flexion: methods and evaluation. Tartu, 1998, 107 p.
3. **Leila Oja.** Physical development and school readiness of children in transition from preschool to school. Tartu, 2002, 147 p.
4. **Helena Gapeyeva.** Knee extensor muscle function after arthroscopic partial meniscectomy. Tartu, 2002, 113 p.
5. **Roomet Viira.** Physical activity, ecological system model determinants and physical self-perception profile in early adolescence. Tartu, 2003, 167 p.
6. **Ando Pehme.** Effect of mechanical loading and ageing on myosin heavy chain turnover rate in fast-twitch skeletal muscle. Tartu, 2004, 121 p.
7. **Priit Kaasik.** Composition and turnover of myofibrillar proteins in volume — overtrained and glucocorticoid caused myopathic skeletal muscle. Tartu, 2004, 123 p.
8. **Jarek Mäestu.** The perceived recovery-stress state and selected hormonal markers of training stress in highly trained male rowers. Tartu, 2004, 109 p.
9. **Karin Alev.** Difference between myosin light and heavy chain isoforms patterns in fast- and slow-twitch skeletal muscle: effect of endurance training. Tartu, 2005, 117 p.
10. **Kristjan Kais.** Precompetitive state anxiety, self-confidence and ahtletic performance in volleyball and basketball players. Tartu, 2005, 99 p.
11. **Aire Leppik.** Changes in anthropometry, somatotype and body composition during puberty: a longitudinal study. Tartu, 2005, 161 p.
12. **Jaan Ereline.** Contractile properties of human skeletal muscles: Association with sports training, fatigue and posttetanic potentiation. Tartu, 2006, 133 p.
13. **Andre Koka.** The role of perceived teacher feedback and perceived learning environment on intrinsic motivation in physical education. Tartu, 2006, 137 p.
14. **Priit Purge.** Performance, mood state and selected hormonal parameters during the rowing season in elite male rowers. Tartu, 2006, 101 p.
15. **Saima Kuu.** Age-related contractile changes in plantarflexor muscles in women: associations with postactivation potentiation and recreational physical activity. Tartu, 2006, 101 p.
16. **Raivo Puhke.** Adaptive changes of myosin isoforms in response to long-term strength training in skeletal muscle of middle-aged persons. Tartu, 2006, 99 p.

17. **Eva-Maria Riso.** The effect of glucocorticoid myopathy, unloading and reloading on the skeletal muscle contractile apparatus and extracellular matrix. Tartu, 2007, 114 p.
18. **Terje Sööt.** Bone mineral values in young females with different physical activity patterns: association with body composition, leg strength and selected hormonal parameters. Tartu, 2007, 94 p.
19. **Karin Tammik.** Neuromuscular function in children with spastic diplegic cerebral palsy. Tartu, 2007, 102 p.
20. **Meeli Saar.** The relationships between anthropometry, physical activity and motor ability in 10–17-year-olds. Tartu, 2008, 96 p.
21. **Triin Pomerants.** Ghrelin concentration in boys at different pubertal stages: relationships with growth factors, bone mineral density and physical activity. Tartu, 2008, 80 p.
22. **Tatjana Kums.** Musculo-skeletal function in young gymnasts: association with training loads and low-back pain. Tartu, 2008, 128 p.
23. **Maret Pihu.** The components of social-cognitive models of motivation in predicting physical activity behaviour among school students. Tartu, 2009, 116 p.
24. **Peep Päll.** Physical activity and motor skill development in children. Tartu, 2009, 102 p.
25. **Milvi Visnapuu.** Relationships of anthropometrical characteristics with basic and specific motor abilities in young handball players. Tartu, 2009, 114 p.
26. **Rita Gruodytė.** Relationships between bone parameters, jumping height and hormonal indices in adolescent female athletes. Tartu, 2010, 82 p.