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Tapani Pöyhönen

Neuromuscular Function During Knee Exercises in Water

With Special Reference to Hydrodynamics and Therapy

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ABSTRACT

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The present series of studies examined neuromuscular function during knee exercise in water and training responses of an aquatic exercise program. Emphasis was placed on the quantification of water resistance, the drag. Subjects who participated in this series of studies were 25-35-year-old healthy women and men. Neuromuscular function was examined using electromyography (EMG), force and reflex sensitivity measurements in the isometric condition on land and in water. EMG and angular velocity were measured during dynamic knee extension-flexion in still and flowing water. The drag forces acting on the leg and foot model were measured in the barefoot condition and with a large resistance boot. The calculated coefficients of drag were then utilised to further calculate the drag forces for the human subjects. Finally, the effects of 10 weeks of aquatic resistance training on isometric and isokinetic torque, EMGs and lean muscle mass (LCSA) were investigated. The results showed lower values for EMG activity and for the EMG/force ratio in water than on land. The same trend was observed for the H- and tendon reflex responses. The EMG patterns in the repeated knee extension-flexion performed in the flowing water demonstrated an early decrease in the concentric activation of the agonists with simultaneous eccentric activation of the antagonists. This indicates stretch-shortening cycle type of exercise whereas the single trial exercises seemed to be purely concentric. The drag forces calculated for the human subjects in knee extension-flexion showed significantly higher values when using the resistance boot than in the barefoot condition with values reaching 210 ± 46 N in men and 146 ± 30 N in women. The forces measured on land were significantly higher than the drag forces in water. Ten weeks of aquatic training resulted in a significant improvement (8-13%) in maximal torque, and this was accompanied with significant increases of 19-27% in the EMGs and 4-6% in the LCSA of the knee extensors and flexors. The results indicated an impairment of neuromuscular function in water, which is possibly due to hydrostatic pressure and the reduced gravity conditions. The results also indicated that by considering the principles of hydrodynamics, and by using additional devices, water resistance can produce a sufficient exercise stimulus to cause positive changes in the neuromuscular system. This will add to the body of knowledge concerning the nature of aquatic exercises and the design of progressive aquatic exercise programs used in rehabilitation and conditioning in water.

Key words: hydrodynamic drag, water immersion, electromyography, reflex sensitivity, aquatic training, muscle torque, muscle mass

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LIST OF ORIGINAL ARTICLES

This thesis is based on the following articles, which will be referred to in the text by their Roman numbers:

I Pöyhönen T, Keskinen KL, Hautala A, Savolainen J, Mälkiä E 1999. Human isometric force production and electromyogram activity of knee extensor muscles in water and on dry land. European Journal of Applied Physiology 80: 52-56.

II Pöyhönen T, Avela J 2002. Effect of water immersion on the neuromuscular function of the plantarflexor muscles: Accepted for publication in Aviation, Space and Environmental Medicine.

III Pöyhönen T, Keskinen K, Hautala A, Mälkiä E 2000. Determination of hydrodynamic drag forces and drag coefficients on human leg/foot model during knee exercise. Clinical Biomechanics 15: 256-260.

IV Pöyhönen T, Kyröläinen H, Keskinen KL, Hautala A, Savolainen J, Mälkiä E 2001 Electromyographic and kinematic analysis of therapeutic knee exercises under water. Clinical Biomechanics 16: 496-504.

V Pöyhönen T, Keskinen KL, Kyröläinen H, Hautala A, Savolainen J, Mälkiä E 2001. Neuromuscular function during therapeutic knee exercises under water. Archives of Physical Medicine and Rehabilitation 82: 1446-1452.

VI Pöyhönen T, Sipilä S, Keskinen KL, Hautala A, Savolainen J, Mälkiä E 2002. Effects of aquatic resistance training on neuromuscular performance in healthy women. Medicine and Science in Sports and Exercise. Accepted for publication.

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LIST OF ORIGINAL ARTICLES

1 INTRODUCTION

The history of hydrotherapy as a modality for curative purposes dates back to 2400BC in the Proto-Indian culture. Later, in 500BC, the ancient Romans produced a series of baths ranging from the coldarium through to the tepidarium and the frigidarium. The bath centers were places where intellectual and recreational activities were pursued, and they were also used for the purposes of hygiene and health, for example, there was an emphasis on the healing of rheumatic diseases and paralysis (Reid Campion 1990). Today, aquatic exercise is an essential part of fitness training as well as physiotherapy, and it is considered to be an effective means of active physical therapy in the rehabilitation of severely injured patients, and even in very fit athletes. Water offers a unique medium where reduced-gravity conditions decrease the loading on joints, while the water itself provides resistance to movements. However, despite the fact that aquatic exercises are widely used, on the basis of the lack of scientific references, the neuromuscular function measured during exercises in water, as well as the responses of aquatic exercise programs on neuromuscular performance, are mostly unknown. In regard to the design of progressive programs for physical conditioning and for therapeutic purposes, there has always been concern about the type, intensity, resistance and duration of the exercises (Basmaijan 1990).

In swimming studies, extensive biomechanical methodologies have been used to determine hydrodynamic forces (e.g. Karpovich 1933, Counsilman 1955, Clarys 1979, Schleihauf 1979, Hollander 1986, Toussaint 1988, Keskinen et al. 1989, Berger 1995) and electromyography (EMG) (e.g. Ikai 1964, Lewillie 1967, Clarys et al. 1985, Rouard et al. 1988, 1990). These have been applied in the analysis of different techniques, as well as in the determination of propulsive forces and water drag during swimming. In hydrotherapy, only a few studies have utilised similar approaches and methodologies. EMG measurements in water have mostly been used to examine the function of the shoulder muscles during swimming (e.g. Perry et al.1992, Pink et al. 1993), or during exercise in water (Fujisawa et al. 1998, Kelly et al. 2000). The quantification of the resistance produced by water during exercises has become a challenge in hydrotherapy to date, and only a few attempts have been made to determine the resistance produced by water for rehabilitation purposes (e.g. Harrison 1980, Prins et al. 1994, Frey Law and Smidt 1996). The responses of aquatic exercise programs on neuromuscular performance, most frequently on muscle strength, have been studied in patients with rheumatoid arthritis, poliomyelitis, as well as in patients with knee and back disorders. To date, however, only few studies have attempted to determine the resistance produced by water, and no work has been done to examine the underlying neuromuscular mechanisms behind the possible improvement in muscle strength that may occur following aquatic exercise programs

A basic knowledge of the interrelationships between hydrodynamics and biomechanical principles is essential to understand human neuromuscular function during underwater exercises so that training programs to progressively overload the neuromuscular system can be effectively planned. Therefore, this thesis was designed to elucidate the nature of aquatic exercises with a special emphasis on the quantification of the resistance produced by water, and then, to determine the relationship between exercises performed in water and on land. In addition, another purpose was to evaluate the effectiveness of an aquatic resistance training program on the neuromuscular performance of the knee extensor and flexor muscles. Single-joint knee extension-flexion was selected as the testing and training exercise, as the biomechanics of the knee joint has been widely analysed. It is also a commonly used mode of therapeutic knee exercise in both dry land and water conditions. The subjects who participated in this project were healthy. The reason for this was that knowledge of muscle function and the resistance of the exercises in healthy persons can provide a framework for the safe application of progressive exercise programmes for therapeutic purposes.

2 REVIEW OF THE LITERATURE

2.1 Water as an exercise medium

2.1.1 Physical properties of water

The Greek mathematician Archimedes (287-212BC) was asked to determine the gold content of King Herold's crown. Archimedes believed that he could determine the volume of the crown by placing it into water and measuring the volume of the fluid that the crown displaced. He also understood that an object immersed in water is acted upon by a counter or buoyant force (upthrust), which helps to support the immersed object against the downward pull of gravity. In addition, a body immersed in water or a liquid seems to lose weight, with the amount being equal to the volume of water displaced. The crown was found to be a fake because it displaced more water than an equal weight of pure gold. (Edlich et al. 1987).

The state of a fluid can be described in terms of its density and pressure. The density of water depends somewhat on pressure, but greatly on temperature. Water is at its maximum density at 4° C (1000 $kg\cdot m^{-3}$), with the value being 998.2 $kg\cdot m^{-3}$ at 20° C (see e.g. Ohanian 1989). The hydrostatic pressure of a fluid is the product of its depth and density. Therefore, hydrostatic pressure increases with increasing fluid depth and density. When the body is submerged underwater, the pressure is the same in all directions at any given depth, and the pressure is also equally distributed over the surfaces of the body lying at the same depth. (Edlich et al. 1987). The hydrodynamic pressure at a depth of 1–2 meters is approximately $1.12 \times 10^5\ N\cdot m^{-2}$, while the pressure at the surface level is $1.0 \times 10^5\ N\cdot m^{-2}$ (see e.g. Ohanian 1989).

Viscosity is a property of fluids, which can be described as follows. Consider a fluid layer sandwiched between two parallel plates with the lower plate being fixed and the upper plate being moved parallel to it at a certain velocity. A force proportional to the velocity is needed to overcome the viscosity of the fluid (Alexander 1977), and therefore, with an increase in velocity, the resistance produced by the viscosity also increases (Roberson and

Crowe 1985). High viscosity can also be defined as the property that makes porridge hard to stir.

When an object is immersed in water it experiences a buoyant force, which is equal to the product of the density of water and the immersed volume of an object, or the volume of the water displaced. This buoyant force acts through the centre of buoyancy while the gravitational force acts through the centre of mass of the body. When floating without extra upthrust, the buoyant force must be equal to the submerged weight of a person. As body density increases, the body starts to sink. Conversely, when the density decreases, the upthrust tends to push the body further out of the water. (Paige 1975). The upward buoyant force and the downward gravitational force do not coincide. Therefore, this generates a torque that is a measure of the tendency of the upper part of the body to rotate around the centre of mass. This can be defined as the underwater torque with which the feet lying horizontally in water tend to sink. (Pendergast and Craig 1974, Paige 1975, Zamparo et al. 1996). In addition, force plate measurements by Harrison and Bulstrode (1986) have shown that when a standing person is immersed in water to the levels of C7, the xiphsternum and the hip, the degree of weight bearing is approximately 10, 30 and 50%, respectively, of the total bodyweight on dry land. Small differences in percentage values exist between the sexes, with females having lower values due to larger amounts of adipose tissue in the body.

2.1.2 Interaction between water and moving objects

Whether focused on juvenile salmon, adult leeches or dolphins, all questions in relation to aquatic locomotion involve, to some degree, the fluid mechanisms of force production. When a fish swims through water with a reciprocating tail fin, it generates forces with its body and creates a distinct wake and vortexes. The forces acting on an animal must be countered by an equal and opposite change in fluid momentum. The tail moves a few chord lengths at a high angle of attack, stops, rotates slightly and repeats the movement in the opposite direction. In each stroke a tail develops force normal to its surface while generating a vortex ring. At the end of the stroke, the tail deposits the old vortex ring in to the wake and starts developing circulation in the other direction. The wake consists of series of rings that continue to move under their own induced velocity spreading the wake laterally. The highest forces are produced during the stroke as the vortex ring grows in size and strength. Finally, there are two basic approaches to the study of movements in water, either focusing on the determination of force production or examining the changes in wake momentum. This is how Dickinson (1996) described the interrelationship between the propulsion forces produced by fish and water dynamics. However, the following chapters concentrate on humans and primarily on hydrodynamic resistance.

A body immersed in flowing or moving water is acted upon by hydrodynamic forces. The sum of these forces that act parallel to the free-stream direction is termed the drag, whereas the sum that acts normal to the free-stream direction is termed the lift. Buoyant and gravitational forces also act on the immersed body, but the drag and lift forces are limited to the forces produced by the dynamic action of the flowing fluid (Roberson and Crowe

1985). According to basic hydrodynamic principles, the flow in which the water travels smoothly and rectilinearly without disturbances can be defined as laminar or streamlined flow. With increased flow velocity, perturbations and eddy (vortex) formation occur until the flow becomes turbulent. (Alexander 1977). In addition, one of the basic features of fluid dynamics, especially in regard to lift, is Bernoulli’s equation or effect, which states that fluid pressure is reduced when the speed of flow increases. For example, when a stream of water passes around a swimmer’s hand, the flow over the convex upper surface has a greater velocity and a lower pressure than on the underside. The difference in pressure between the two streams creates the lift. This same principle of lift is also what supports aircraft in flight (Counsilman 1971, Colwin 1991). An object moving through water displaces some water out of its path. This reaction of the water to the moving object appears as pressure and frictional forces. For a swimmer, therefore, when travelling in the state of “hydrostatic weightlessness”, the major part of the mechanical work is aimed to overcome the hydrodynamic resistance.

Drag can be defined as a resistant force opposite to the direction of movement of an object. Total drag is mainly composed of pressure drag and frictional drag. A swimmer also experiences resistance from the air on the above-water parts of the body, as well as wave making resistance. Calculations of the contribution of the total hydrodynamic resistance revealed that frictional drag is about 1-2% of the pressure resistance, while wave-making resistance is less than 5% of the pressure drag (Alexander 1977, Vorontsov and Rumyantsev 2000). Figure 1 illustrates the drag, buoyant and gravitational (mg) forces acting on the moving leg during knee extension in water.

It is apparent that the streamlines around an object can move at different velocities, thus creating a velocity gradient in the passing flow. The streamlines adjoining the surface of the object forms a boundary layer, which is composed of a number of thin layers interacting with each other. The first layer sticks to the skin, and the friction between this layer of particles and the object slows down the velocity of the streamline, which travels at the same velocity as a swimmer.

Each successive layer then flows more easily and with a greater velocity than the previous one until the state of free flow is achieved. The effect of these viscous forces on the surface of a moving object can be defined as frictional or viscous drag. The surface of an object such as skin has main influence on the friction resistance because it modifies the formation of eddies in the boundary layer. The rougher the skin, the greater the friction, which in part increases the formation of eddies. This enhances boundary layer turbulence, thereby causing resistance and increasingly opposes the movement (Alexander 1977, Colwin 1992).

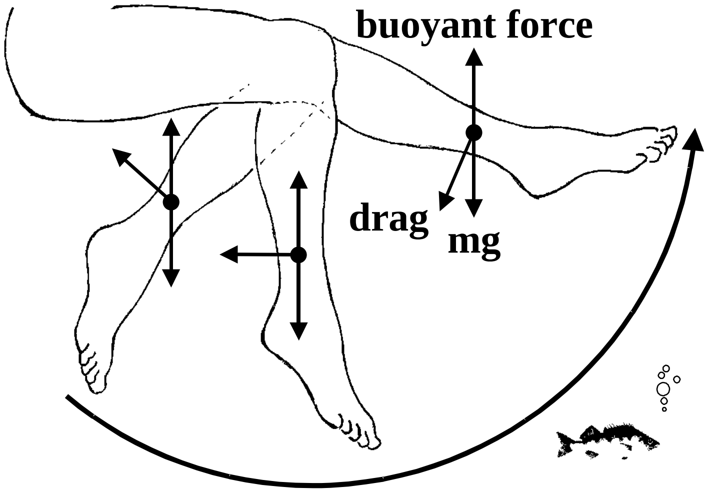

FIGURE 1 A schematic presentation of forces acting on the moving leg during knee extension underwater (mg = mass x gravity).

A streamlined object moving with low velocity induces little or no turbulence in the state of laminar flow. In this condition, the total resistance is primarily determined by frictional drag. On the other hand, the increase in velocity and alteration in the form of the object create turbulent flow, which then has a great impact on pressure resistance. This resistance is a result of the pressure gradient between high pressure on the front side, and low pressure behind the moving object. This is due to the flow of water within the boundary layers, which are separated from each other before they reach the rear of an object. The separated layers then induce eddies, which rotate the water masses with high velocity, and an area of low pressure is formed behind the object. Turbulence is generated by the mass of water that is sucked along behind an object in the form of retarding eddies or vortexes. The pressure drag, which is also called eddy resistance, is proportional to the size, shape and angle of the frontal area that is being pushed against the water flow. Therefore, this drag is also called form drag. The relationship between the drag force and the velocity of movement is non-linear, with the drag increasing as a function of velocity squared (v^2). This means that when the speed of a moving object doubles, the consequent drag force quadruples. In addition, the angle of attack, which is the angle at which the swimmer meets the water, is a crucial factor in the determination of the interaction of drag and lift forces during swimming. Since the projection of the swimmer or the swimmer’s hand in the direction of movement increases with the angle of attack, the resistance acting on a swimmer increases (Alexander 1977, Barthels 1979, Schleihauf 1979, Colwin 1992).

Circulatory forces exist around moving objects, and these are sources of lift, in particular, as well as drag, and they require the formation of vortexes. More specifically, a vortex or a vortex loop, in common usage, means a whirlpool or a circular cavity formed by rotating water. In addition, a vortex is a form of kinetic energy, and without resistance provided by vortex turbulence in water, no tactive force would be provided. When an object starts to move or changes direction, an eddy sheet can be observed, and this is referred to as a starting vortex. A vortex cannot be created without a counter-vortex of equal strength circulating in the opposite direction. This is a bound vortex, which is responsible for the production of lift, which is explained by Bernoulli`s equation that indicates the pressure differential between the upper and lower sides of the object. For a swimmer, induced drag is a result of the altered velocity and pressure distribution around the extremity. For example, the high and low pressure streams meet at the trailing edge of the swimmer’s hand, crossing each other to form a trailing vortex. The energy utilised in the formation of the vortex trail then appears as the induced drag. To increase the speed of movements, extra thrust is needed to overcome the resistance caused by induced drag. In addition, the shedding of the laterally moving vortexes creates a change in pressure with a consequent side thrust, which causes “swinging” of the moving object in water (Alexander 1977, Colwin 1992, Dickinson 1996, Arellano 1999).

Bodily movements can be performed against still water (no flow) or with flowing water. For example, competitive swimmers continuously try to find resistance from still water to push against, in order to gain support for forward movement, while at the same time trying to avoid working against the moving water (Counsilman 1969). Whether focused on swimming or aquatic exercises performed in different flow conditions, the amount of water mass to be accelerated or decelerated, in addition to the body-segments themselves, has been called ”the added mass”. Movement of the body segments accelerates the water mass that surrounds the body parts, and this results in increased resistance to movements. The magnitude of the added mass has been shown to depend on the size, shape, and flow pattern surrounding the moving extremity (Klauck 1999).

During aquatic exercises, such as knee extension-flexion, where the leg movement opposes the buoyancy and the created drag produced by the water tends to increase. Therefore, the buoyant forces, in particular, and to some degree the lift forces, should be carefully considered when designing underwater hydrotherapy programs. These forces can be used in three ways: as resistive forces, as assistive forces, or as supportive forces to the movement. In order to optimally use the buoyant forces as a resistance, the limb is moved, from a floating horizontal position, downwards through water (Golland 1981, Edlich et al. 1987). Therefore, the angle at which the moving extremity meets the upwardly directed buoyant force determines the resistance. At large angles, drag increases, and vice versa, at small angles it decreases (Edlich 1987). During knee extension-flexion performed in water, the more the upward thrust is reduced, and the angle of attack is decreased, the nearer the moving extremity gets to the vertical position. In addition to the buoyant forces, the lift forces act on the moving extremity, especially during the final range of motion when the orientation of the leg is beneficial to the assistive forces. Increasing the speed of movement and the length of the lever arm can further increase drag and enhance muscular work (Golland 1981). Therefore, by varying the velocity, and by using external devices to change the form of the extremity being exercised, increases or decreases in pressure drag, in particular, which is the major contributor of the total resistance as explained earlier, can be achieved.

In the literature numerous books and articles have been published that deal with the principles of hydrodynamics or swimming. However, among different authors, there are some small discrepancies in the terms and explanations used for hydrodynamics. With increasing amount of research work using up-to-date measurement methods, it seems that in the future new theories and concepts will be presented.

2.1.3 Determination of passive and active drag forces

In swimming research, drag forces have been divided into passive and active drag. The former is the resistance produced by water which an object experiences in an unchanging posture such as during passive towing or when performing gliding without movements, and the latter is the water resistance related to the active swimming motion (Clarys et al. 1974). Many researchers have determined passive drag mostly by measuring the resultant total water resistance in relation to velocity. Karpovich (1933) was among the first to measure passive drag force with a spring scale while towing swimmers with the use of an electrical motor, and a resistograph in a pool. Thereafter, several methods have been used, for example, tethered swimming, which is easy to use but differed from actual swimming (Lewillie 1971). Further modification of the resistograph was used by Alley (1952) and Counsilman (1955). Miyashita and Tsunoda (1978) measured hydrodynamic resistance in a flume with the swimmer's body being exposed to an water flow created by a propeller. The swimmer was connected to the measurement device by a cable and this enabled the posture of the swimmer to be observed.

In the series of studies by Clarys (1974, 1975) and Jiskoot & Clarys (1975), swimmers were towed through water in order to determine passive drag, and further, Clarys et al. (1979) determined active drag. The results showed that the resistance is greater underwater than at the surface, and that the relationship between body shape and passive drag increases with increasing velocity. It was also found that at higher temperatures the passive and active drag were smaller when compared to the respective values measured at temperatures 5-6°C lower. However, the effect of temperature decreases with increasing velocity. Their results also indicated that active drag was 1.5-2.0 times greater than passive drag, and that body shape, with its composition or the skin surface area, does not influence active drag. Active drag is influenced by changes in position and by the movement of the different body segments. Swimming technique, therefore, has an influence on the amount of hydrodynamic resistance. Some years earlier, Di Prampero et al. (1974) indirectly estimated active drag during actual swimming based on the determination of a swimmer's oxygen uptake. A method for the direct measurement of active drag called the MAD system ("Measuring Active Drag") was developed by Hollander et al. (1986). The MAD system recorded the forces applied to push-off pads underwater, and so simulated the front crawl arm action (Toussaint et al. 1988). Kolmogorov & Duplisheva (1997) used the velocity perturbation method, in which the maximal velocity of swimming was changed using added drag that was induced by a hydrodynamic body of known resistance towed by the swimmer. In addition to previous methods, pressure measurements have also been used to determine segmental propulsion during swimming. For example, in a recent study, Toussaint et al. (2002) used modified disposable blood pressure transducers on the shoulder, arm and hand to clarify the importance of axial flow around the arm during the rotational insweep and outsweep phases. They found a pressure gradient along the arm, with the palm of the hand demonstrating the highest values. Together with other measurements, they concluded that axial flow during the rotational outsweep phase of the stroke in front crawl swimming enhances propulsion by increasing the pressure difference over the hand.

The hydrodynamic forces acting on an object can be determined as a function of its velocity in the fluid, its surface area and the density of the fluid based on the following fluid equations (e.g. Alexander 1977):

$$F_d = 1/2\rho \cdot A \cdot v^2 \cdot C_d$$

$$F_l = 1/2\rho \cdot A \cdot v^2 \cdot C_l$$

where ρ is fluid density, A is the projected frontal area of the object, v is the velocity, C_d is the drag, and C_l is the lift coefficient. C_d is related to the shape, streamlining, and the Reynolds number of an object (velocity in $m \cdot s^{-1}$ x length in m), which in human body is in the range of $6.6 \times 10^5 < R < 3.9 \times 10^6$ (Clarys 1985), as well as to the angle of attack during swimming. If the total drag force is measured, for example, with a force dynamometer, C_d can be calculated according to the previous equations. Schleihauf (1979) measured drag and lift forces on human arm models in a flow channel in order to determine coefficients of lift and drag. He combined these results with the hand velocity data obtained from motion analysis of swimmers and calculated the magnitude and direction of the propulsive force during the stroke cycle with the equations presented earlier. Scleihauf (1979) reported that the largest resultant force generated by the hand and arm was 190 N. More recently, Berger et al. (1995) replicated the study of Scleihauf (1979) by towing two models of hands and forearms in a towing tank and determined the coefficients of the drag and lift forces, and these were similar with those of Scleichauf et al. (1979). Furthermore, Berger at al. (1997) calculated the hydrodynamic forces generated by the hands and forearms by using three-dimensional analysis in actual swimming and the general fluid equations. They found that the largest propulsive forces were 128 N, which were somewhat smaller than those calculated by Scleihauf (1979).

Only a few attempts to determine the resistance of water have been made for rehabilitation purposes. In 1980, Harrison presented a method to quantify the resistance in water exercises with the use of polystyrene floats. Later, Hillman et al. (1987) determined the resistance to motion through water using table-tennis bats. In their study, a pair of strain gauges was attached to the bat, and the amplified electrical signal from the strain gauges was proportional to the load of the table-tennis bat. Prins et al. (1994) tested dynamic force production underwater during different exercises with a measurement system consisting of a differential pressure transducer attached to the exercising limb or resistive device. The general fluid equation was applied for hydrotherapy purposes in the study by Frey Law and Smidt (1996) who experimentally determined the force production of an upper body resistance device at its two primary orientations, as well as at different water flow velocities.

The interesting fact is that somewhat controversial results dealing with the magnitude of passive and active drag have been reported, thus indicating the differences between measurement systems. In hydrotherapy, it was more than twenty years ago when Harrison (1980) stated two requirements for strengthening exercises in the pool. These were that the therapist should know the “weight” which loads the muscle in any particular water exercise, and he/she should be able to relate the water exercise to an equivalent exercise on land. However, the lack of references to date indicates that quantification of water resistance during therapeutic exercises still seems to be the future challenge of hydrotherapy.

2.2 Neuromuscular function in water

2.2.1 Use of electromyography (EMG) in water conditions

Electromyography can be defined as “The study of muscle function through the inquiry of the electrical signal the muscles emanate” (Basmajian and De Luca 1985). An activation of muscle fibres results in a temporo-spatial spread of electric potentials within and across the surface of the muscle. These potentials are commonly recorded in a bipolar electrode configuration, by two electrodes; on the surface of the skin and in the muscle (intra-muscular EMG). Thereby, the electrical potential difference is measured. The EMG measurements are highly dependent on the specific demands of the type of subjects being measured, the specific demand of the field circumstances, such an aquatic environment, and the normalising technique used to reduce variability between subjects or different trials (De Luca 1997, Clarys 2000).

In numerous studies, the reproducibility coefficients of EMG measurements have been determined for various types of muscles and muscle actions (e.g. De Vries 1968, Komi and Buskirk 1970, Yang and Winter 1983, Arsenault et al. 1986, Gollhofer et al. 1990, Heinonen et al. 1994). Despite the different methods used to calculate the reliability of the EMG measurements, it can be concluded that the within day reproducibility is somewhat better than the day-to-day reproducibility. However, no studies seem to be available, which consider the reliability of neuromuscular measurements performed in controlled, underwater conditions.

Several studies have reported somewhat controversial results in regard to the effects of movement velocity and the type of muscle action on EMG activity. Basically, the force-velocity curve in the concentric condition indicates that muscle force decreases when the shortening velocity increases. With respect to EMG activity, during concentric muscle action, higher EMG activity occurs when the movement velocity increases (e.g. Aagaard et al. 2000, Komi et al. 2000), whereas in eccentric muscle action, the velocity of the movements does not seem to have an influence on EMG activity (Komi et al. 1973, Aagaard et al. 2000). When comparing the effects of muscle action on EMG activity, during concentric and eccentric muscle actions maximal EMG activity seems to be at the same level (Komi and Buskirk 1972, Komi 1973, Komi et al. 2000), increased in concentric muscle actions (Eloranta and Komi 1980, Tesch et al. 1990, Westing et al. 1991), and activity during concentric muscle action exceeds that produced during isometric muscle activity (Komi et al. 2000).

While muscle function and kinematics during different swimming styles have been extensively studied with adequate underwater methodologies, only a few similar biomechanical approaches exist with regard to therapeutic exercises underwater. Ikai et al. (1964) were the pioneers in the recording of underwater EMG signals in swimmers in relation to their swimming technique. Lewillie (1968) introduced techniques using telemetry-based EMG**.** Okamoto and Wolf (1980) found good correlations between the fine wire and surface electrodes in underwater EMG recordings. Clarys et al. (1985) made comparisons between conventional and telemeter underwater EMG, and found that signal amplitude was smaller when measured telemetrically compared to using traditional methods. They also reported that signal amplitude underwater was decreased when compared to dry land conditions during maximal isometric muscle contractions. Rouard et al. (e.g. 1988, 1990, 1995) published several EMG and kinematic studies in freestyle swimming. Wakayoshi et al. (1994) utilised EMG methodology to investigate muscle fatigue phenomenon at high intensity swimming and concluded that EMG analysis could provide a valuable method to determine the degree of fatigue in muscles during actual swimming. Dietz et al. (e. g. 1989, 1996) used underwater surface EMG measurements and a moving force platform to investigate the significance of gravity in the generation of postural adjustments. The buoyancy of the body underwater simulated the effect of weightlessness. With respect to the quantified EMG of the tibialis anterior and gastrocnemius medialis muscles, the results indicated lower amplitudes underwater when compared to similar conditions out of water. A decline of the EMG amplitudes was observed in different levels of immersion. They concluded that the enhanced influence of proprioception from the pressure receptors in water seemed to control the function of reflexes in water. Sato et al. (1999) compared Hoffman-reflex excitability (H-reflex) during standing in water and on land. They found that the H-reflex response was higher in reduced gravity conditions underwater, and concluded that the increasing action potentials come from muscle proprioceptive factor, because the neural afferents are deactivated by reduced gravity load.

In the area of sports medicine and rehabilitation, Perry et al. (e.g. 1992) and Pink et al. (e.g. 1993), in their series of studies, used indwelling electromyography electrodes and cinematography to compare muscle activity, as well as timing of the muscle action of normal and painful shoulders, during different swimming styles. Aquatic exercises of the shoulder have been examined with underwater EMG technology by Fujisawa et al. (1998) and Kelly et al. (2000) who studied shoulder muscle activation in aquatic and dry land exercises in non-impaired subjects during isometric (Fujisawa et al. 1998) and dynamic (Kelly et al. 2000) conditions. They reported that the EMG activity of underwater exercises was decreased compared to similar exercises performed on dry land. No other EMG studies dealing with underwater exercise seem to be available.

According to Clarys (1993), no other sport has taken advantage of EMG since the 1960s when the first EMG recordings underwater were performed. Today, EMG measurements are extensively used in swimming science. However, surprisingly, few studies in physical therapy have utilised underwater EMG measurements to examine muscle function during water exercises.

2.3 Effects of aquatic exercise programs on neuromuscular function

The low impact nature of exercise in water has gained interest in this form of training. The level of research interest in neuromuscular responses and mechanisms has been scant compared with water running which can be used as an alternative modality to maintain land-based performance levels (Frangolias and Rhodes 1996). The effects of aquatic training programs on neuromuscular performance have mostly been studied in different patient groups and in elderly persons. There is evidence that aquatic rehabilitation has been beneficial in pathological situations and in persons with low levels of physical fitness. For example, aquatic exercises have led to improved muscle strength and endurance levels in elderly people (Ruoti et al. 1994), in persons with multiple sclerosis (Gehlsen et al. 1984), as well as in persons with poliomyelitis disability (Prins et al. 1994, Willen et al. 2001). Furthermore, according to several studies, aquatic rehabilitation programs have resulted in improvements in strength and aerobic capacity in patients suffering from rheumatoid arthritis (Danneskjold-Samsoe et al. 1987, Stenström et al. 1991) and fibromyalgia syndrome (Mannerkorpi et al. 2000). LeFort and Hannah (1994) reported that, in patients with low-back injuries, a combined aqua-fitness and muscle-strengthening exercise program was beneficial as measured by physical indices. Taunton et al. (1996) studied the effects of land-based and water-based exercise programs on cardiovascular fitness, muscle strength and flexibility in older women. They found no improvements in muscular strength and concluded that both types of exercise venues had similar effects on the measured parameters.

In respect to aquatic exercises for the knee, Tovin et al. (1994) compared the effects of land- and water-based rehabilitation following anterior cruciate ligament (ACL) surgery. Isokinetic and isometric torque measurements showed no differences in quadriceps muscle performance, whereas in the land group, greater torque of the hamstrings was recorded. Recently, Petrick et al. (2001) compared eight weeks of quadriceps muscle strengthening on land and in water in young healthy women. They found that there were no significant differences in strength improvement, which was measured with an isokinetic dynamometer at angular velocities of 60 and 270 deg·s^{-1}, between the water and land exercise groups after eight weeks of training. Significantly more subjects in the land group complained about pain while exercising compared to the water exercise group.

According to previous studies it is somewhat difficult to design comparable exercise regimens in water and on land. In addition, only a few studies have attempted to estimate the resistance produced by water during exercises. Finally, it seems that no studies have examined the underlying neuromuscular mechanisms that explain the possible improvements in muscle performance after aquatic exercise programs.

3 PURPOSE OF THE STUDY

As shown by the previous review of the literature, research in the field of therapeutic exercises in water is scant. Therefore, the general aim of this thesis was to elucidate neuromuscular function of exercises in water and the training responses of aquatic exercise program. This series of studies also attempted to determine the relationships between exercises performed on land and in water. More specifically, the aims of this thesis can be expressed as follows:

1) To determine the day-to-day and trial-to-trial reproducibility of EMG and isometric force measurements of the knee extensor muscles for water and land conditions, and to compare the measured signal amplitudes between these two conditions. The aim was also to compare the signals of EMG, force, H- and tendon reflexes of the plantarflexor muscles between water and land conditions. (I and II).,

2) To measure hydrodynamic drag forces on the human leg/foot model in barefoot and hydro-boot conditions, and accordingly, to determine the coefficients of drag during simulated knee extension – flexion (III).

3) To evaluate muscle activity patterns and kinematics during single trial and repeated trial barefoot knee extension-flexion in two water flow conditions: the single trial was initiated against still water and the repeated trials were performed against flowing water resulting from leg movements (IV).

4) To quantify drag forces in humans and to compare the neuromuscular function (EMG, forces) between the barefoot and hydro-boot conditions, as well as between the exercises performed underwater (barefoot, hydro-boot) and on land (isometric, isokinetic) (V).

5) To study the effects of 10 weeks of aquatic resistance training on neuromuscular performance (EMG, isometric and isokinetic torque) and the muscle mass of the knee extensors and flexors in healthy women (VI).

4 MATERIALS AND METHODS

4.1 Subjects

A total of 68 volunteer subjects participated in these studies. All the subjects were healthy with no contraindications for participation in the experiments, and they were fully informed about the measurement procedures and possible risks involved. They gave their written informed consent before each study. The studies was approved by the Central Hospital of Kymenlaakso Ethics Committee. The subjects were habitually active with regular weekly participation in physical activity (2-3 times a week, 35-60 minutes per session). Table 1 shows the physical characteristics of the subjects in the five experimental series.

TABLE 1 Physical characteristics of the subjects in studies I, II, IV, V, VI (mean, SD)

	Age (yrs)	Height (m)	Body mass (kg)
Study I			
Women (n=12)	32.3 (5.5)	1.66 (0.02)	61.3 (4.7)
Men (n=8)	28.0 (4.8)	1.83 (0.03)	79.5 (7.5)
Study II			
Men (n=6)	23.2 (5.1)	1.82 (0.04)	83.2 (5.9)
Study IV, V			
Women (n=10)	25.3 (4.5)	1.66 (0.05)	59.3 (4.1)
Men (n=8)	28.0 (4.8)	1.81 (0.07)	79.7 (7.5)
Study VI			
Training women (n=12)	33.8 (3.9)	1.65 (0.03)	60.6 (4.9)
Control women (n=12)	34.7 (3.9)	1.68 (0.05)	64.8 (4.9)

4.2 Study design

4.2.1 Reproducibility of EMG and isometric force

In order to evaluate the measurement methodology on land and in water, the day-to-day and trial-to-trial reproducibility of EMG and isometric force measurements during knee extension were determined (Study I). In addition, the amplitudes of the recorded signals were compared between these two conditions. The EMGs were measured from the quadriceps and hamstring muscles. The subjects visited the measurement laboratory three times over a two-week period, with a period of at least 48 hours separating the measurement sessions.

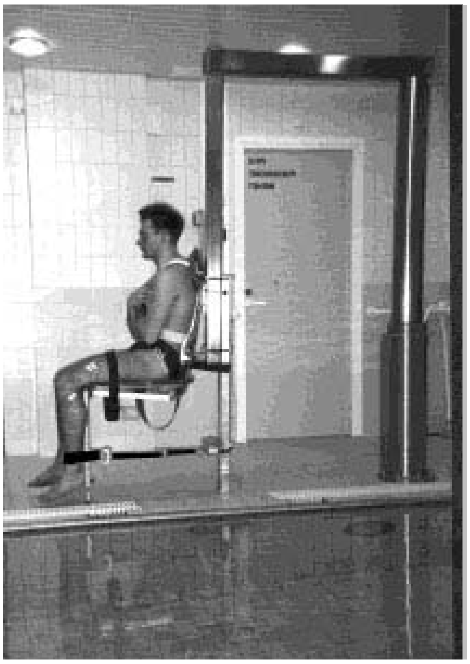

FIGURE 2 The patient elevator chair at the poolside and the set up for the measurements of isometric knee extension force.

The three measurement sessions for each of the subjects were performed at the same time of the day. During each of the measurement days, the subjects performed identical maximal and submaximal isometric force tests with simultaneous EMG recordings performed on dry land and in water. The subjects were asked to avoid vigorous exercise during the 24-hour period prior to the measurement sessions. Of the subjects, ten were randomly selected to start the first session on dry land. The treatment order was changed in the next two sessions. Measurements were performed using the same patient elevator chair at the poolside and in the therapeutic pool as shown in Figure 2 (Studies I, II, IV, V, VI). The chair was lowered into the pool so that the water surface was at the mid-sternum level. The room and water temperatures were 26° and 29° C, respectively, during the measurement days.

The subjects were carefully familiarised with the test procedure and trained to produce maximal force output for knee extension before each measurement session. The warm-up period, which was also used in Studies IV, V and VI, on dry land was standardised as follows: 10 minutes of cycling on a stationary bicycle ergometer at a heart rate of 120-130 beats·min^{-1} plus four minutes of stretching exercises for the lower legs (Studies, IV, V, VI). Before the measurements in the water, the subject walked about for 3 minutes in the pool in order to get used to the new conditions. Thereafter, the isometric force exerted by the dominant leg was measured by a dynamometer in the patient elevator chair. The knee and hip angles were set at 90° and securing straps were used to fix the thigh and hip while sitting in the measurement chair. After two sub-maximal repetitions, the subjects were instructed to perform the muscle contraction (4 seconds) as fast and as hard as possible. Verbal encouragement was used to motivate the subjects to reach their maximum. The time between the contractions was 60 seconds. Three repetitions were performed and the largest force was recorded as the peak force contraction. After a 3-minute rest, the subjects were asked to hold one sub-maximal contraction at a force level of 150 N in women and 250 N in men. This sub-maximal force for the women ranged from 30 to 48%, and from 34 to 53% for the men, of the maximal isometric knee extension force measured at a knee angle of 90°. Visual feedback was used only in the sub-maximal contractions. The time interval between these two sessions was 10 minutes.

4.2.2 EMG, isometric force and reflex sensitivity of the plantarflexors

In order to obtain more detailed information about neuromuscular function underwater, Study II was designed to compare the measured signals of EMG, isometric force, tendon- and H- reflexes of the plantarflexor muscles between the dry land and water conditions. A tendon reflex is a monosynaptic, ipsilateral spinal reflex, which is activated by stretching the muscle spindles, which in turn facilitate the contraction of the agonist muscles and inhibition of the antagonists (Matthews 1964). The tendon reflex depends on both α-motoneuron excitability and muscle spindle sensitivity. The H-reflex is similar to the monosynaptic stretch reflex, but it is elicited by bypassing the muscle spindle and directly electrically stimulating the afferent nerve instead of stretching the muscle spindle. The H-reflex is considered to mainly evaluate the excitatory drive to the α-motoneuron pool (Bishop et al. 1968, Capaday 1997). The plantarflexors were chosen because the H-reflex is mostly measured from the soleus muscle, and the repeatability of the reflex measurements of the plantarflexors is better than when measured from the quadriceps.

Recordings were conducted using an ankle ergometer, which was a modified poolside patient elevator chair (Fig. 2). The identical testing procedure was first performed on dry land and then in water with the water surface being at the level of the mid-sternum for each subject. The room and water temperatures were standardized at 26 and 30°C, respectively, in order to ensure similar skin temperatures between the dry and wet conditions. The skin temperatures (calf, thigh) measured in four subjects were 0.35 ± 0.19°C lower in water. The subjects were seated in the elevator chair with the knee angle set at 20° flexion. The hip, thigh and leg were stabilised with straps to prevent movement that could affect the measurements. The dynamometer was attached around the forefoot as shown in Figure 6 (p. 36). A three minute adaptation time to the water conditions was allowed for each subject between consecutive measurements to avoid any fatique and/or post-contraction effects. The maximal isometric force (MVC) of the plantarflexors was measured first, and this was followed by measurements of 50% MVC, H- and Achilles tendon reflexes.

4.2.3 Drag forces on the leg/foot model

The rationale to use the leg model in Study III to measure segmental drag forces, and accordingly to determine the coefficients of drag, was based on the studies conducted by Schleihauf (1979) and Berger (1994, 1997). They used the models of human arms to calculate the drag coefficients and further utilised the C_d values in the general fluid equation in actual swimming. Therefore, a rubber covered prosthesis filled with wax was made to simulate the adult human leg and foot segment in the knee extension – flexion movement in Study III. The length, weight and projected frontal area of the model were 0.5 m, 4.8 kg and 0.07 m^2, respectively. The ankle of the model was placed in 20 degrees of plantar flexion, which demonstrated the average of the motion analysis data in four human subjects (two males, two females). The movement of the ankles of the subjects during knee extension-flexion was videotaped underwater and the mean angle was determined by motion analysis. Twenty degrees was found to correlate best to the full ROM. The leg and foot model was set in an 800-liter tank of water. The immersion depth and the ROM of the model are shown in Figure 3.

The prosthesis was attached to an isokinetic dynamometer (Biodex Corp, Shirley, USA) with a fixture arm through the wall of the tank. The set - up was water resistant and no extra rotational friction affected the fixture arm. The direction of movement of the prosthesis and the ROM simulated the knee extension - flexion movemente and the ROM of the model was adjusted from 180° of knee flexion to full extension. The measurements were first performed in the barefoot condition and then with the hydro-boot (Hydro-Tone Fitness Systems, Inc., Huntington Beach, CA, USA), which was attached around the lower leg of the model.

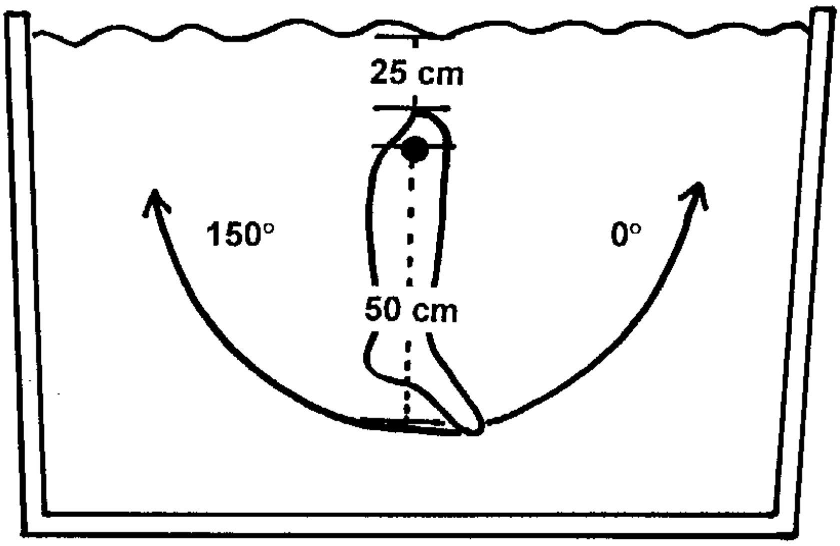

FIGURE 3 A schematic picture of an 800-liter water tank and the model of the human foot and leg attached to the dynamometer. The length of the prosthesis, the immersion depth and the ROM are shown in the figure.

4.2.4 EMG and angular velocity in single and repeated knee exercises

In order to evaluate EMG patterns and angular velocity in two water flow conditions in Study IV, the single trial was initiated against still water and the repeated trials were performed against flowing water resulting from leg movements. During the first visit to the laboratory, the participants were carefully familiarised with the testing procedure and were trained to execute maximal dynamic efforts during free movement in water. The actual measurements were performed during their second visit. The left leg of each subject was tested because of the location of the underwater camera system.

The underwater recordings of EMG from the quadriceps and hamstrings, as well as simultaneous videotaping, were performed after the warm-up period (see p. 25). Measurements were made in a poolside patient elevator chair as shown in Figure 2. Fixation straps were placed around the hip and thigh to prevent additional movements. The hip angle was set at 90° of flexion, and knee ROM for each subject was limited by adjusting the measurement chair to a range from 120° of knee flexion to full extension (0°). After familiarisation in the aquatic environment, the participants performed four to six sub-maximal, warm-up repetitions as single extension and flexion efforts. Thereafter, the participants performed the single extension and flexion exercises twice against still water with the maximal efforts separated by 20-second intervals. The identical testing of the single extension and flexion movements was repeated after a one-minute recovery. After two minutes of rest, the participants performed eight repeated extension-flexion movements with sub-maximal effort. The actual testing consisted of six to eight maximal knee extension -

flexion repetitions and the participants were instructed to execute the movements throughout the whole ROM. Verbal encouragement was given during the trials.

4.2.5 EMG and resistive forces in water and on land

In Study V, special emphasis was placed on the quantification of drag forces acting on the lower leg of the human subjects during repeated knee extension-flexion in barefoot and hydro-boot conditions. In addition, the comparisons between the underwater and dry land forces and corresponding EMG patterns were made. The isometric measurements were first performed followed by isokinetic and underwater ones. On dry land, the measurements were performed using an isokinetic dynamometer. The EMGs were measured from the knee extensor and flexor muscles. After the warm-up period (see p. 25), the subjects were fixed into the test position of 90° of hip flexion and 90° of knee flexion with straps. After sub-maximal repetitions, the subjects were instructed to perform three maximal isometric extensions (4 seconds) in an explosive manner. The recovery time between the contractions was 60 seconds. Verbal encouragement was used to motivate the subjects to reach their maximal effort levels. After a 2-minute rest period, the subjects repeated the identical testing protocol for maximal isometric flexion.

In the isokinetic measurements, the subjects were fixed into the test position of 90° of hip flexion and the lever arm of the dynamometer was attached 2 cm above the mid-line of the malleolus lateralis. The subjects performed four sub-maximal and two maximal concentric knee extension-flexion efforts on the dynamometer as a warm-up for the isokinetic testing. The actual testing protocol consisted of six maximal extension-flexion repetitions at a constant angular velocity of 180 $deg \cdot s^{-1}$ representing power-type torque production. Knee ROM was limited from 115° of knee flexion to full extension (0°).

Underwater measurements were firstly performed in the barefoot condition (see 4.2.4) and then with a hydro-boot, which was attached to the leg and foot (Fig. 4, p. 31). The projected frontal area of the hydro-boot was 0.0750 m^2 and provided a similar level of resistance in both the extension and flexion directions. The enlargement of the frontal area of the lower leg with hydro-boot was from 30 to 35% as compared to the barefoot condition. The subjects performed four to six sub-maximal repeated extension-flexion movements in the barefoot condition. During the actual testing, the subjects then performed 6-8 maximal efforts. After two minutes of rest, the identical testing procedure was repeated with the hydro-boot.

4.2.6 Aquatic training procedure

In the final experiment (VI) of the present thesis, the study of the effects of 10 weeks of progressive aquatic resistance training on neuromuscular performance and muscle mass was conducted in healthy women. The measurements were performed 3-4 days before and after the training period. In addition, to control the training program, the women in the exercise group underwent additional measurements at the beginning of the fifth training week. The exercise group participated in a 10-week aquatic resistance training program. The subjects in both groups were asked to maintain their current level of physical activity throughout the 10-week period. To ensure that this was achieved, the participants were instructed to keep physical activity diaries that included information on the types and duration of the physical activities performed.

The maximal isometric and isokinetic torques and EMGs of the knee extensors and flexors were measured using an isokinetic dynamometer. Before the measurement session, the subjects were carefully familiarized with the testing procedure and were trained for the maximal isometric and isokinetic efforts using the left leg. After the warm-up (see p. 25), the subjects were positioned on the dynamometer and fixed tightly by straps in 90° of hip flexion and 60° of knee flexion. After a few sub-maximal repetitions, the subjects were instructed to perform two maximal isometric extension and flexion movements (4 seconds) in an explosive manner. The recovery time between the efforts was 60 seconds, and 2 minutes between the extension and flexion movements. Verbal encouragement was used.

Thereafter, as a pre-test warm-up for the isokinetic testing, the subjects performed four submaximal and two maximal concentric knee extension-flexion efforts on the isokinetic dynamometer. The actual testing protocol consisted of four to six maximal extension-flexion repetitions at constant angular velocities of 60 and 180 $deg \cdot s^{-1}$, respectively. The measurements with the slower contraction velocity represent maximal-type torque of the muscle group, while the faster velocity measurements represent power-type torque production. The ROM of the knee was limited to a range from 115° of knee flexion to full extension (0°).

4.2.7 Aquatic training program

The 10-week aquatic training was specifically directed at improving the neuromuscular performance of the quadriceps and hamstring muscle groups. All training sessions during the 10 weeks were conducted in small groups of 4-5 persons, and these were supervised by an experienced instructor. Each session started with a 6-8 min warm up including aqua jogging using floating belts (Aqua Jogger, USA) and stretching exercises for the lower extremity muscles. This was followed by 30-45 minutes of resistance training, and then a 5 minute cool-down period. The present exercises were selected on the basis of the current available knowledge on muscle function and drag forces for knee exercises performed underwater (Study V). Each training session consisted of four primary exercises for both legs: 1) repeated one leg knee extension-flexion movements in a sitting position, 2) repeated one leg knee extension-flexion in a standing position, 3) reciprocal knee extension-flexion movements in a sitting position and 4) either a hip extension- flexion movement with extended knee in a standing position or “water kicking”, in which the knee was extended during hip flexion and flexed during hip extension. These two movements in exercise 4 were alternated each training session. In water, the effect of the movement velocity on the resistance produced by water is emphasised. When the velocity doubles the drag produced by water quadruples. Therefore, the subjects in the exercise group were instructed to perform each repetition during exercise sessions with maximal effort in order to achieve the highest possible movement velocity and subsequent resistance. Verbal encouragement by the instructor was provided.

Table 2 summarises the training program, including the weekly sessions, sets, duration of work and rest, training time a week, and resistance produced by the resistance boots. Training time for each week was determined as follows: work + rest of each set and repetition of both legs. The progression of the training program was ensured by using three different sized resistance-boots (small, medium, large), and by varying the amounts of sets and duration of the exercises, which were equal for each subject. The small Aqua Runners Zero Impact Footwear (Aqua Jogger, USA) attached around the foot of the subject was used during the initial two weeks of training in order to technically practice the exercises. Thereafter, the actual strength training in water was conducted using the medium and large resistance boots (Hydro-Tone hydro-boots, Hydro-Tone Fitness Systems, Inc., Huntington Beach, CA, USA) with frontal areas of 0.045 and 0.075 m^2, respectively. The structure of these boots allowed similar resistance to both extension and flexion directions.

TABLE 2. The summary of the 10- week aquatic training program used in the present study (rep = repetition).

Week	Sessions / set	Sets / session	Reps / set	Work / rep	Rest / rep (s)	Time / wk (min)	Boot size	Drag (N)
1	2	2	20-25	20	30	24	small	65 ± 20
2	2	2	20-25	25	35	30	small	65 ± 20
3	3	3	14-20	20	35	28	medium	112 ± 24
4	3	3	14-20	20	35	43	medium	112 ± 24
5	3	3	14-20	25	40	50	medium	112 ± 24
6	3	3	14-20	30	50	58	medium	112 ± 24
7	3	3	12-15	25	45	52	large	160 ± 32
8	3	3	12-15	30	50	58	large	160 ± 32
9	3	3	12-15	35	50	66	large	160 ± 32
10	3	3	12-15	35	50	66	large	160 ± 32

In order to estimate the intensity of the training, the water resistance was calculated, and the velocity of the movements and heart rate responses during the exercises were measured. The peak drag force generated by each participant was determined using the general fluid equation, which will be thoroughly explained in chapter 4.3.3. Figure 4 shows the experimental set-up during seated knee extension-flexion with hydro-boot. The drag values of each subject were determined during the third training week. The average peak drag values for extension and flexion for the small, medium and large resistance boots are presented in Table 2. The average peak angular velocities during extension and flexion with the small, medium and large resistance boots were 420 ± 22, 315 ± 26 and 162 ± 20 deg·s^{-1}, respectively. The heart rate responses of the subjects were monitored continuously during the training sessions using heart rate monitors (Polar Sport Tester, Polar Electro, Kempele, Finland) to control the level of work and recovery. The average heart rates during the exertion period of the sessions with the medium and large resistance boots were 127 ± 11 and 125 ± 12 beats·min^{-1}, respectively.

FIGURE 4 Seated unilateral knee extension-flexion exercise with a large hydro-boot underwater.

4.3 Measurements and analyses

4.3.1 Isometric and isokinetic force and torque

In Studies I and II, isometric force in dry land and water conditions was measured on the patient elevator chair with a waterproof strain gauge dynamometer (range 0-2000 N, sampling rate 1000 Hz), which was integrated with the 8-channel EMG system (see 4.3.2). The dynamometer was attached around the ankle, 2.5 cm above the mid-point of malleolus lateralis (Study I) and around the foot as seen in Figure 6 (p. 36) (Study II). Calibrations were performed before each measurement session. Maximal force of the best effort was chosen for analysis.

Measurements of the maximal isometric (Studies IV, V, VI) and isokinetic (Studies V, VI) torque of the knee extensors and flexors were performed using a Biodex (Shirley, NY, USA) isokinetic dynamometer. The sampling frequency was 100 Hz with a 1% measurement error through the entire range of motion. The axis of rotation of the dynamometer was carefully aligned with the lateral femoral condyle. The lever arm of the dynamometer was attached around the ankle, 2.5 cm above the mid-point of malleolus lateralis. During isokinetic testing, the weight of the limb and the lever arm of the dynamometer were considered to correct for the effects of gravity. The dynamometer was calibrated before each measurement session according to the standard procedure recommended by the manufacturer using the standard calibration weight. The peak torque of the best effort was analysed. The isokinetic and the isometric torque values (Study V) obtained from the dynamometer in Newton meters (Nm) were further divided by the length of the shank of each subject to obtain force in Newtons (N) to make the values comparable to those for underwater drag forces. In addition, the isometric knee extension-flexion force-time curve for the exercise group was produced using 50-ms intervals for the first 500 ms in Study VI. For the isometric and isokinetic torque measurements, the day-to-day reproducibility, which was determined by calculating the intra-class correlation coefficients (ICC), varied between .94 and .98. With the present sample size, the statistical power of detecting a significant interaction was from 79 % and 92 % for isometric and isokinetic peak torque measurements.

4.3.2 Electromyography

In Studies I, II, IV, V and VI, EMG was recorded telemetrically with an eight channel EMG system (Mespec 4000, Mega Electronics, Kuopio, Finland) from the vastus medialis, vastus lateralis, biceps femoris and semitendinosus muscles (Study I, IV, V, VI). EMG was measured from the soleus and medial gastrocnemius muscles in Study II. Oval-shaped bipolar pre-gelled silver chloride surface electrodes (Medicotest N-OO-S, Denmark), of width 2.1 cm and length 2.9 cm, were placed between the distal motor point and the tendon longitudinally along the muscle fibres. In addition, bipolar fine wire electrodes were used to obtain internal EMG recordings from the soleus of three subjects (Study II). Figure 5 presents the raw EMGs of the medial gastrocnemius measured with surface and fine wire electrodes in water and on land. The inter-electrode distance was 2.0 cm. To keep the inter-electrode resistance low (<2 kΩ), the skin was shaved, rubbed with sandpaper and cleaned with 60% alcohol. Resistance was determined before and after each measurement with a digital multi-meter. In Study I, for example, each muscle showed smaller values after the measurements (2.2 kΩ before, with no contraindications for participation, and 1.4 kΩ afterwards). No extra protection, other than waterproof taping on the electrodes, was used. The positions of the electrodes were marked on the skin with indelible ink to ensure the same electrode position for each session. The ICC coefficients varied between .86 and .96 for the EMG measurements. With the present sample size, the statistical power of detecting a significant interaction was from 70 to 72% for the EMG measurements.

In Studies I, IV and V, a hole in the seat of the measurement chair was made to protect the electrodes on the hamstring muscles from pressure. A similar set-up was made on the measurement chair of the isokinetic dynamometer in Studies V and VI.

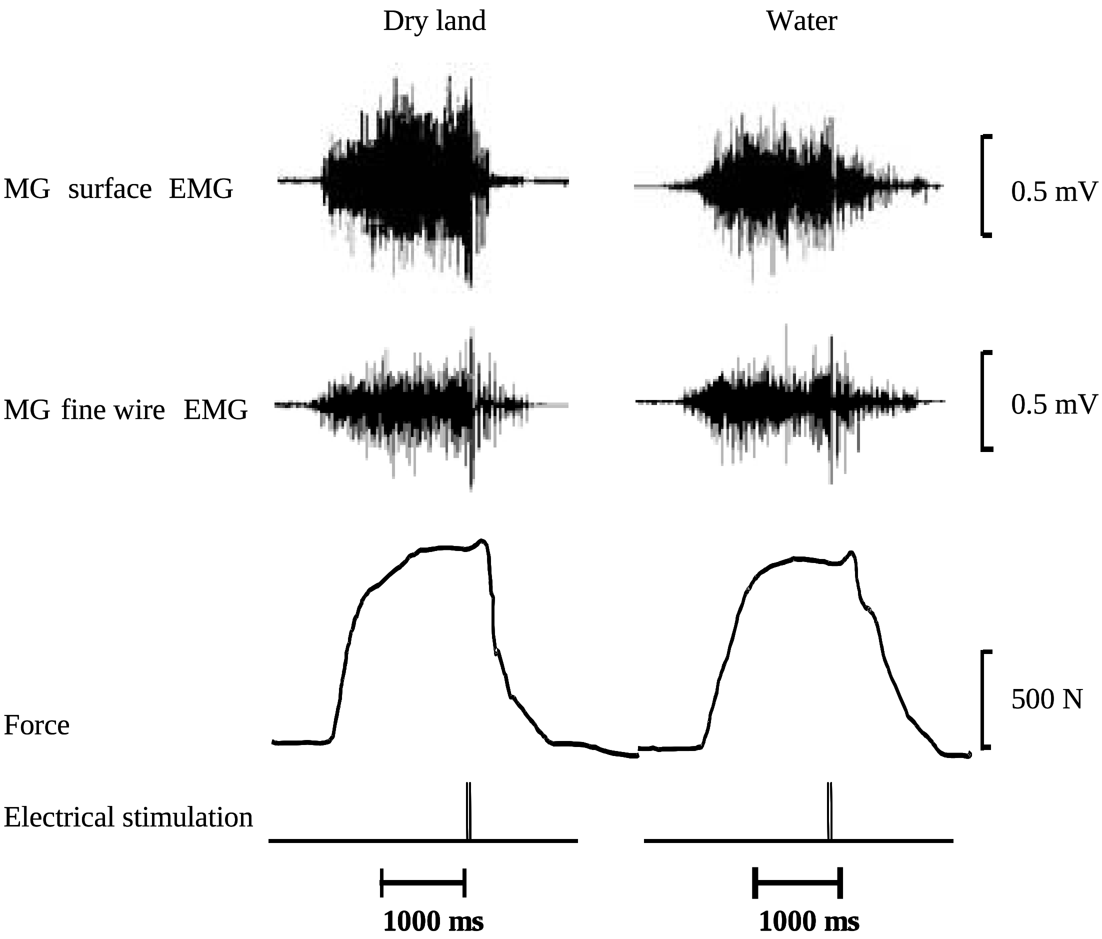

FIGURE 5 MVC data from one subject illustrating the effects of head-out water immersion. EMG was measured with surface and fine wire electrodes from the medial gastrocnemius muscle (MG). There is a cut-off in the EMG signal at the onset of electrical stimulation.

The performances for further analysis were selected according to the highest isometric force and isokinetic torque values. The recorded EMG signals were pre-amplified by the telemeter transmitter with a gain of 1000. The signals were carried through a different amplifier with an input impedance of 10 GΩ, a common mode rejection ratio > 100 dB, and a signal-to-noise ratio of 72 dB. Filtering of the raw EMG was performed with low and high pass filters (Butterworth type), with the bandwidth between 20 and 500 Hz in surface electrodes, and 1 kHz in fine wire electrodes. The raw EMG signal was passed through a 12-bit A-D converter with a 1000 Hz sampling frequency, and then transferred to a computer for further analysis. Background noise in the filtered signal was less than 1 µV. The measured EMG signal was full wave rectified and the average amplitude (aEMG) of the signal was calculated in the isometric, isokinetic and in underwater recordings. In the maximal isometric contractions, the window width of 500-1500 ms or 1000-2000 ms from the starting point of the force or torque curve was analysed (Studies I, V, VI). The selected window was dependent on the timing of the peak force/torque. In the maximal isometric force (MVC) measurements of the plantarflexors (Study II), the average of the EMG signal was calculated using a 1000 ms window, which was positioned so that the peak force occurred in the middle of the window. In the sub-maximal isometric contractions, a 1-3 second section according to the force curve was analysed (Studies I, II). The criteria was that the force should remain steady and that it should not be within the first and last 10% of the contraction time. In the isokinetic and underwater measurements (Studies IV, V), the rectified EMG signal was averaged with a 20 ms time constant during the entire ROM. In Study VI, maximal aEMG during isokinetic efforts was analysed in the range between 50 ms before and 50 ms after the peak torque value. The electrode placement and the processing of the EMG signal were performed in accordance with the European recommendations for surface electromyography (SENIAM 1999).

In Study IV, EMG and video synchronisation was managed so that the videotape was time coded with 25 impulses/second. Correspondingly, the EMG signal included the respective time information. The software matched the time code of the video with timing of the EMG so that one frame in the video corresponded to 20 samples of the EMG. Thus, one EMG value was an average of 20 samples. For the repeated knee extension-flexion movements, the ROM was from 118° - 0° during extension and from 0° - 117° during flexion. Consequently, the underwater EMG and angular velocity data were divided into 11 phases, the first one corresponding to 15° (from 115° - 100°), and thereafter into ten phases with each interval representing 10° degrees (from 100° - 0°) of the knee flexion angle.

4.3.3 Drag forces and coefficients on the leg/foot model

In Study III, the motor of the power-head of the isokinetic dynamometer produced a preset constant angular velocity (passive mode) to rotate the leg/foot prosthesis with torque measured simultaneously. The initial passive preset velocities of the present dynamometers were from 5 to 150 $\text{deg}\cdot\text{s}^{-1}$. However, in the present study, the speeds were doubled to better correspond with the normal angular velocities of the human knee joint. After doubling of the speeds, the movement of the model was videotaped to check each velocity by motion analysis (Mikromak, Erlangen, Germany). The final velocities used in the experiment were 250, 270 and 300 $\text{deg}\cdot\text{s}^{-1}$, respectively. The reason for the use of several angular velocities within a narrow range was to ascertain the stability and feasibility of the force measurements and related drag coefficients. The ROM analysed was from 150° to 20° in the barefoot condition, and from 140° to 20° in the hydro-boot condition, in order to exclude the initial acceleration phase at the start and the final force ”overshoot” at the end of the movement. The underwater weight of the prosthesis was preset to zero in the computer program of the dynamometer. The isokinetic dynamometer was calibrated before each measurement session. The measured torque values obtained from the dynamometer in Newton meters (Nm) were divided by the length of the prosthesis to obtain force in Newtons (N). Based on the force values obtained from the dynamometer, the coefficients of drag (C_d) on the model were calculated according to the general fluid equation ($F_d = 0.5 \cdot \rho \cdot A \cdot v^2 \cdot C_d$) as follows:

$$C_d = F_d \ / \ 0.5 \, \rho \, \nu^2 \, A$$

where F_d is the drag force (N) obtained by the dynamometer, ρ is the density of water (998.6 $kg \cdot m^{-3}$), ν is the velocity of the model ($m \cdot s^{-1}$), and A is the projected frontal area of the prosthesis. Angular velocity (ω) was transformed into linear velocity (ν) as follows:

$$\nu = \omega \, 2 \, \pi \cdot r \ / \ 360$$

where ω is angular velocity in $deg \cdot s^{-1}$, π is 3.14, and r is the radius or length of the model (0.5 m). According to equation, the linear velocity translations for the angular velocities of 250, 270 and 300 $deg \cdot s^{-1}$ were 2.18, 2.36 and 2.60 $m \cdot s^{-1}$, respectively. The values of the forces and drag coefficients are presented in relation to the knee angles for the ROM from 150 to 20° of knee flexion, using 10° increments.

4.3.4 Reflex sensitivity

The testing protocol in Study II included 3 maximal isometric plantarflexion efforts (MVC) with a superimposed double twitch in order to test the activation level (Merton 1954), 50% MVC, and measurements of H- and Achilles tendon reflexes. The standard methodology was used to record the Hoffmann (H) reflex. After preparing the skin, stimulation electrodes (pregelifiees AG/AGCL electrodes, Niko, Denmark) were positioned for the H-reflex and M-wave testing. The M-wave represents the EMG recorded in response to direct stimulation of the α-motoneuron and the M_{max} is the maximal compound motor unit action potential (Hugon 1973). The position of the stimulus electrodes was tested first in an upright standing position, and then checked in the experimental position to ensure constant recording conditions. The cathode (1.5 x 1.5 cm) was placed over the tibial nerve in the popliteal fossa and the anode (5 x 8 cm) was placed superior to the patella. For the H-reflex, and M-wave testing single rectangular pulses of 1 ms duration, were delivered from a signal generator of the evoked-potential measuring system (MEB-5304K, Nihon Kohden, Japan). The H-reflex and M-wave recording signals were also amplified, stored and analysed by the evoked-potential measuring system. Each pair of EMG and stimulation electrodes was isolated from the surrounding water environment using transparent adhesive film and water resistant taping.

In the tendon reflex measurements, having the waterproof reflex hammer move with a constant rate of acceleration ensured comparable tendon strikes in the two testing conditions. Acceleration was measured with an accelerometer attached to the reflex hammer (Fig. 6)

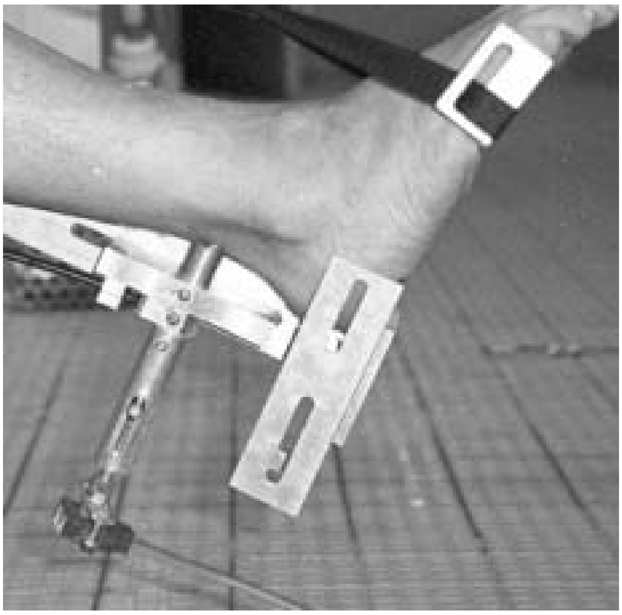

FIGURE 6 The set-up for force measurements of the Achilles tendon reflexes. A waterproof reflex hammer with an accelerometer and dynamometer attachment around the forefoot.

For the analysis of the Achilles tendon reflexes, three trials were performed with the highest reflex forces being selected. The peak-to-peak amplitudes of the EMG and force were determined and the EMG-force ratio was calculated. In the H-reflex measurements, maximal H-reflex peak-to-peak amplitudes were expressed in relation to the maximal M-wave peak-to-peak amplitudes. From the single twitches, which were induced by the maximal M-wave, peak twitch torque (PTT) was analysed.

4.3.5 Determination of drag forces on human subjects

In Studies V and VI, the underwater drag forces during the ROM were calculated according to the general fluid equation (see p. 35). The projected area was measured according to the silhouette lines drawn manually from the leg and the foot in the barefoot and hydro-boot conditions. In Study V, the mean of the projected area of the lower leg used for the drag force calculations was significantly ($p<0.001$) larger in men than in women in both the barefoot condition (0.096 ± 0.006 m^2 and 0.074 ± 0.004 m^2) and with the hydro-boot (0.118 ± 0.004 m^2 and 0.111 ± 0.004 m^2), respectively. The coefficients of drag for the barefoot and hydro-boot conditions obtained from Study III were used in the calculations.

Motion analysis in Studies V and VI. To obtain a sagittal view of the lateral side of the left lower leg and foot, an underwater video camera (50 Hz frame rate) was used. The camera system was attached to an electrically moveable arm at the side of the pool. The optical axis of the camera was parallel to the bottom of the pool and perpendicular to the plane of knee motion. The lens of the camera was approximately 3 m from the object and 0.50 m below the water surface. The optical field was about 1.3-1.5 m wide in the plane of motion. A shutter speed of 0.02 seconds was selected. Markers (2.0 cm diameter) were painted on three bony landmarks on the left lower limb of the subjects: the lateral aspect of the greater trochanter, the lateral femoral epicondyle, and the malleolus lateralis. Video images of the knee extension and flexion movements were digitised automatically and corrected manually throughout the range of motion using a Mikromak Motion Analysis System. The measured distance between the lateral femoral epicondyle and malleolus lateralis was used to calibrate the video images for each subject. ROM and angular velocity were obtained from the motion analysis data. The measured angular velocities (ω) during each condition were further transformed into linear velocities (v) (see 4.3.3, p. 35).

4.3.6 Computed Tomography (CT)

In Study VI, CT scans were obtained from the mid-thigh from the side of the left leg using a Siemens Somatom DR scanner (Siemens AG, Erlangen, Germany). Mid-thigh was defined as the midpoint between the greater trochanter and the lateral joint line of the knee. The distance from the floor to the measuring sites was recorded and used for the follow-up measurements. Lean tissue cross-sectional area (LCSA) and mean density of the lean tissue (Houndsfield unit, HU) were measured for the quadriceps femoris and the hamstrings by a measurer who was not aware of the subjects' groups. The coefficient of variation between the two consecutive measurements varied between 1 and 2% for the LCSA and was less than 1 % for the mean HU of the muscle lean tissue (Sipilä and Suominen 1996). With the present sample size, the statistical power of detecting a significant interaction was from 85 to 92% for the CT measurements.

4.4 Statistical analyses

Standard procedures were used to calculate means, standard deviations (SD), standard errors of means (SE_M) and the coefficients of variation (CV).

In Studies I, IV, V and VI, reproducibility for each variable was determined using repeated measures ANOVA to calculate intra-class correlation coefficients (ICC). The purpose of the ICCs were to estimate systematic error and variance, which would have been affected by systematic changes in the measurements. ICC determines the relative reliability.

Confidence intervals of 95% were also calculated for ICCs. In Study I, the intra-subject coefficient of variation (CV_{intra}) was calculated. The CV_{intra} is the root mean square error over all trials as a percentage of the mean of the observations and it estimates the magnitude of pure measurement error. In addition, standard error of measurements (SEM) was determined using the following equation SEM = SD x (1-ICC). CV_{intra} and SEM analyse the absolute reliability of the measurements.

Normality of the data distribution was tested using the Shapiro-Wilk's W-test (Studies I, II, V and VI). Accordingly, a two-tailed paired Student's t-test (Study I), or the non-parametric Wilcoxon Signed Ranks-test were used to analyse the differences between measurement conditions because of low number of subjects in Study II. In study V, the t-test for independent samples and the Mann-Whitney U test for EMG data were used to compare the male and female subjects. The differences between the test conditions for the strength parameters were assessed by using ANOVA for repeated measures, and Friedman's 2-way ANOVA was employed for the EMG data. If the significance was less than .05, the difference between the conditions was localised by using a paired t-test or the Wilcoxon Signed Ranks-test.

In Study VI, the statistical differences in the baseline measurements between the exercise and control groups were determined using the t-test for independent samples. The effects of the training program and differences between the baselines to mid- and post-training measurements within exercise group were assessed using ANOVA for repeated measures, and Friedman's 2-way ANOVA was used to analyse the EMG data. The level of significance level was set at $p< 0.05$. All statistical analyses were performed through the use of a statistical software package (SPSS, Version 8.0, SPSS Inc., USA).

5 RESULTS

This section shows the major findings obtained from the present series of studies. For additional details the original papers (I-VI) should be consulted.

5.1 Neuromuscular function during isometric actions in water and on land

5.1.1 Reproducibility of EMG and isometric force measurements

The day-to-day reproducibility coefficients (ICC and 95% CI), CV_{intra} and SEM of the EMGs and isometric forces during maximal knee extension in water and on land are shown in Table 3. The trial-to-trial ICC and CV_{intra} values for the maximal contractions ranged from 0.95 to 0.99 and from 3.5 to 11.2%, respectively. For the submaximal contractions the ICC and CV_{intra} values ranged from 0.90 to 0.97, and from 12.7 to 17.4%, respectively in the two test conditions.

TABLE 3 Day to day reproducibility of isometric force, vastus lateralis, vastus medialis and biceps femoris muscles between the three measurement days. (ICC = intraclass correlation coefficient, CI 95% = 95-per-cent confidence interval, CV_{intra} = intrasubject coefficient of variation, SEM = standard error of measurement)

	Condition	ICC	CI 95%	CV (%)	SEM
Isometric force	Land	0.98	0.94-0.99	11.9	16.9 N
	Water	0.96	0.92-0.98	11.3	23.1 N
Vastus medialis	Land	0.95	0.90-0.97	11.9	13.9 µV
	Water	0.94	0.89-0.96	11.3	16.1 µV
Vastus lateralis	Land	0.97	0.94-0.98	13.7	18.8 µV
	Water	0.97	0.94-0.98	15.0	18.4 µV
Biceps femoris	Land	0.90	0.83-0.92	14.3	2.6 µV
	Water	0.85	0.74-0.89	19.2	2.4 µV

5.1.2 EMG and isometric force amplitudes during knee extension

A statistically significant difference was found between aEMG amplitudes for the maximal (p= 0.01-0.001) as shown in Figure 7 (upper part) and submaximal (p= 0.05-0.001) contractions in dry and in water conditions, with the dry land values demonstrating the highest values. The decrease of aEMG amplitudes in water was 11-17% in the vastus medialis and vastus lateralis muscles while the respective decrease in the antagonist biceps femoris was 17-25%. The isometric force production of the knee extensors for the maximal contractions did not show significant differences among the three different measurement sessions on land and in water (Fig. 7, lower part).

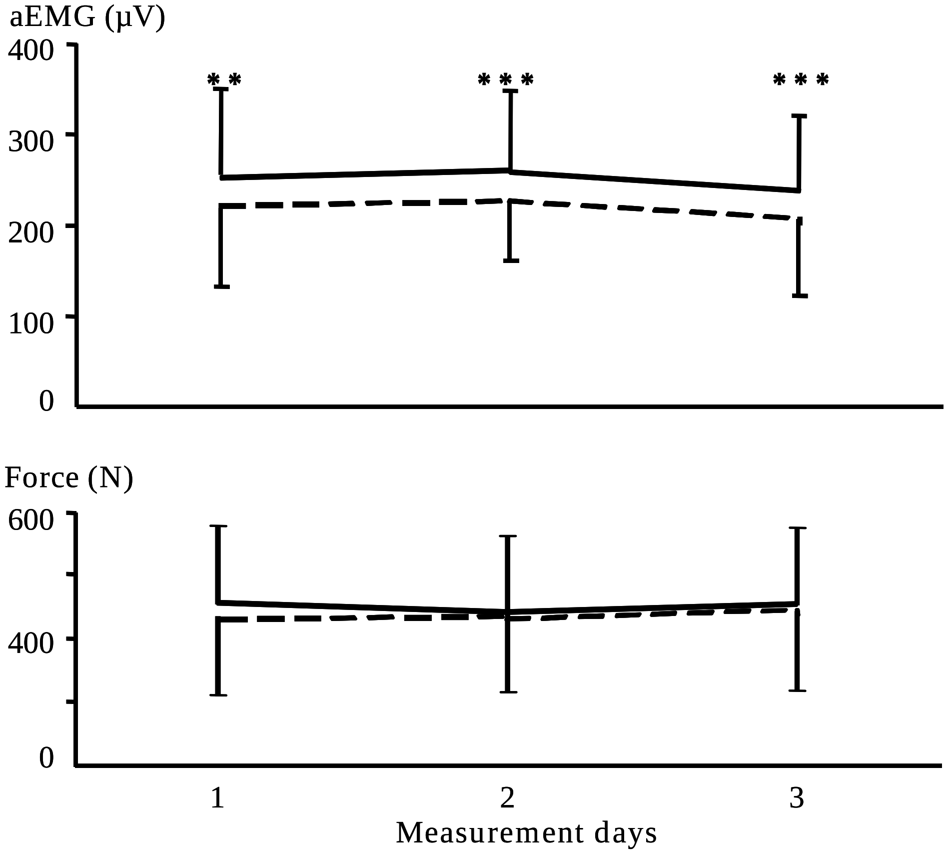

FIGURE 7 Mean (SD) muscle activity (μV) of the quadriceps (vastus medialis + vastus lateralis / 2) in maximal isometric contractions on dry land (solid line) and in water (dashed line) (above). The relation between maximal isometric force (N) on land and (solid line) and in the water (dashed line) during the three measurement days (below). (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$)

5.1.3 EMG, isometric force and reflex sensitivity of plantarflexors

In the plantarflexor muscles, the maximal isometric force decreased by -13.8 ± 4.8%. The activation level during MVC showed non-significant difference between dry (98.5 ± 1.6%) and water (96.6 ± 5.3%) conditions. The related aEMG activities of the medial gastrocnemius (MG) and soleus (SOL) muscles decreased by 29.0 ± 13.6% ($p = 0.042$) and 34.8 ± 7.9% ($p = 0.035$), respectively. The decrease in MG and SOL aEMG/force ratios during maximal contractions were 21.5 ± 8.7% ($p = 0.050$) and 24.2 ± 10% ($p = 0.042$), respectively. Similar trend was observed in MG and SOL muscles during 50% of MVC. The decrease in the EMG activity of the SOL was similar, when measured with fine wire electrodes in three subjects as compared to the measurements with surface electrodes.

While no differences were found in the mean tendon reflex forces between dry and water conditions, the relative reductions observed for the peak-to-peak EMG responses of the tendon reflexes in water were 30.1 ± 6.5% for MG, and 27.7± 13.4% for SOL. The maximal H/M ratio decreased by 31.0 ± 26.1%.(Fig. 8). This reduction was due to a lowered H-reflex amplitude, since the maximal M-wave showed similarity between dry and water conditions. However, the peak twitch torque (PTT) measured under water increased by 11.7 ± 8.7% as compared to the corresponding measurement on land.

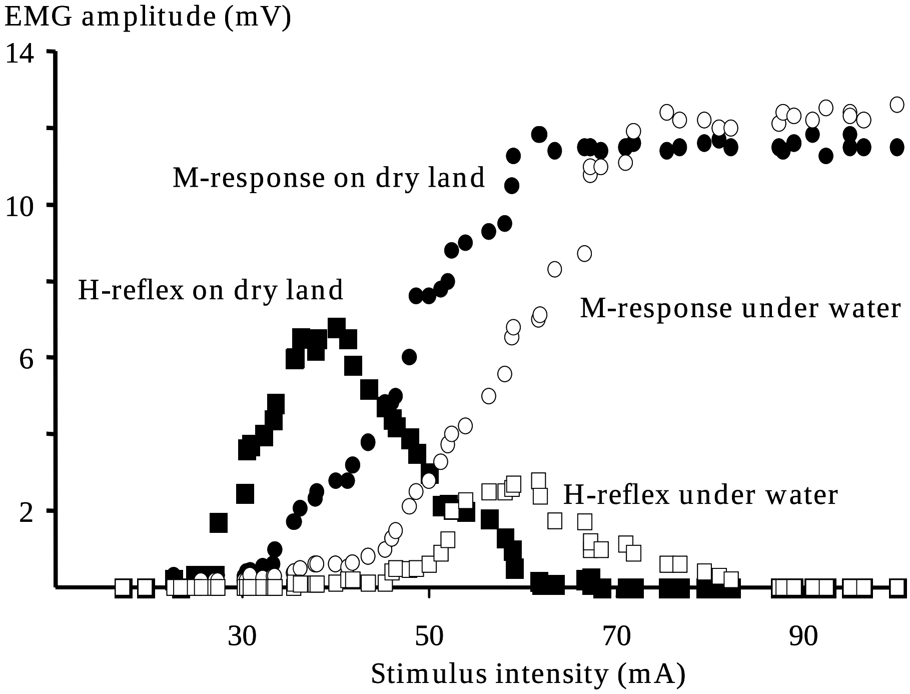

FIGURE 8 An example of the relationship between the H-reflex (square) and the M-wave responses (circle) on dry land (filled) and under water (unfilled) as a function of the stimulus intensity in one subject.

5.2 Drag forces and coefficients of the leg/foot model

The measurements with the leg and foot model were performed on two consecutive days in order to determine the day-to-day CV. The CVs for force curves during the whole ROM (150-20°, 10° increments) varied between 1.1 and 1.7%. The force curves recorded at two different angular velocities (250 and 270 deg·s^{-1}) during the barefoot condition and with the hydro-boot, are shown in Figure 9. The force values are presented in relation to the "knee" angle of the leg and foot model and the highest values of 60 N in barefoot and 270 N in hydro-boot were measured.

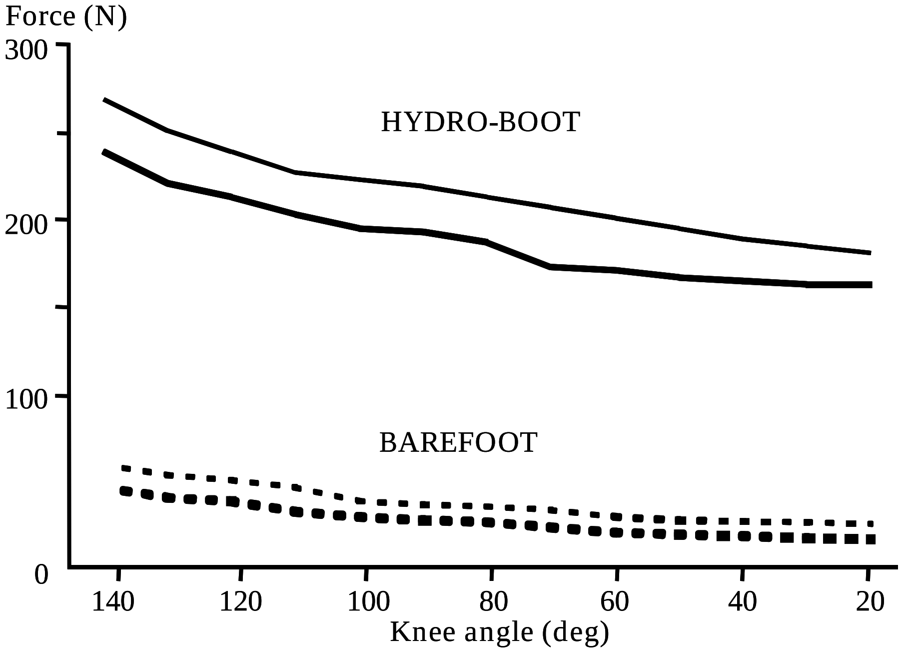

FIGURE 9 The measured drag force curves (N) of the leg and foot model at the angular velocities of 250 (thick lines) and 270 deg·s^{-1} (thin lines) in the barefoot and hydro-boot conditions at varying knee angles for simulating underwater knee extension.

Table 4 shows the calculated coefficients of drag (C_d) for the barefoot model and respective values for the model with hydro-boot. These results are utilised to calculate drag forces for human subjects in the chapter 5.3.2.

TABLE 4 The coefficients of drag (C_d) for the barefoot and hydro-boot leg and foot model at different knee angles during the extension and flexion movements.

Extension			Flexion		
Knee flexion. angle (deg)	C_d Barefoot	C_d Hydro-boot	Knee flexion angle (deg)	C_d Barefoot	C_d Hydro-boot
140	0.27	1.00	20	0.26	0.92
130	0.24	0.95	30	0.24	0.88
120	0.22	0.91	40	0.21	0.84
110	0.20	0.89	50	0.19	0.80
100	0.18	0.88	60	0.17	0.74
90	0.17	0.84	70	0.16	0.73
80	0.15	0.80	80	0.14	0.70
70	0.14	0.74	90	0.14	0.69
60	0.13	0.73	100	0.12	0.69
50	0.12	0.70	110	0.12	0.68
40	0.11	0.69	120	0.12	0.68
30	0.11	0.69	130	0.11	0.67
20	0.11	0.68	140	0.11	0.66

5.3 Neuromuscular function during dynamic knee extension-flexion

5.3.1 EMG patterns and angular velocity during single and repeated trials

Figure 10 illustrates the EMG activity patterns during the single extension and flexion efforts in men and women. The EMG activity of the quadriceps and hamstring muscles was relatively high in the pre-activation phase in both subject groups. In the extension movement, the high EMG activity bursts of the agonist muscles were observed during the early part of the ROM while the muscle activity of the antagonists was low during the ROM in both subject groups. During the single flexion efforts, the EMG patterns were similar as compared to the respective patterns recorded during extension as presented in Figure 10.

During the extension phase in the repeated exercise, the peak EMG activity of the quadriceps occurred during the early part of the ROM and declined during the final part of the ROM in both groups, as illustrated in Figure 11. The antagonistic hamstring EMGs during the extension phase started to increase early. Similarly, the activity of the hamstrings declined during the initial ROM in the flexion phase with a concurrent increase in the activity of the quadriceps, as the antagonist muscle group (Fig. 12).

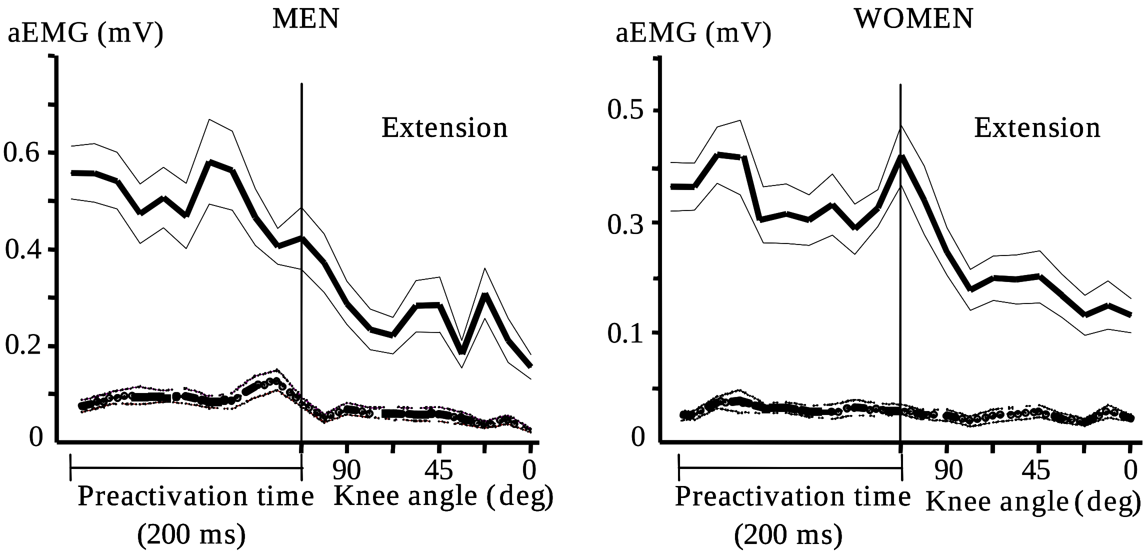

FIGURE 10 Mean (±SE_M) aEMG patterns of the quadriceps (upper solid lines) and hamstrings (lower dashed lines) during pre- activation and single trial extension movement in men and women.

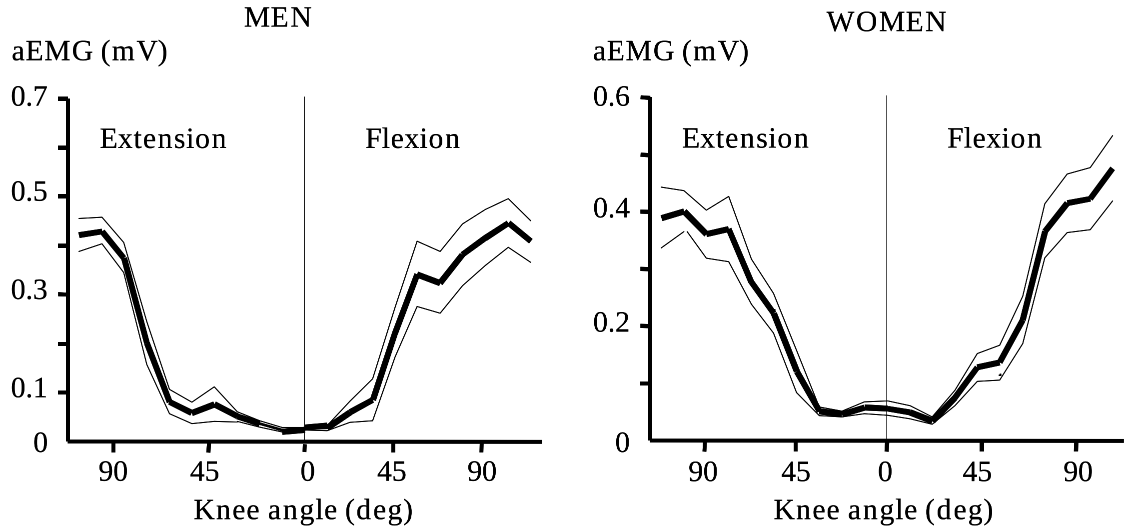

FIGURE 11 Mean (± SE_M) aEMG activity pattern of the quadriceps during repeated barefoot knee extension- flexion in men and women.

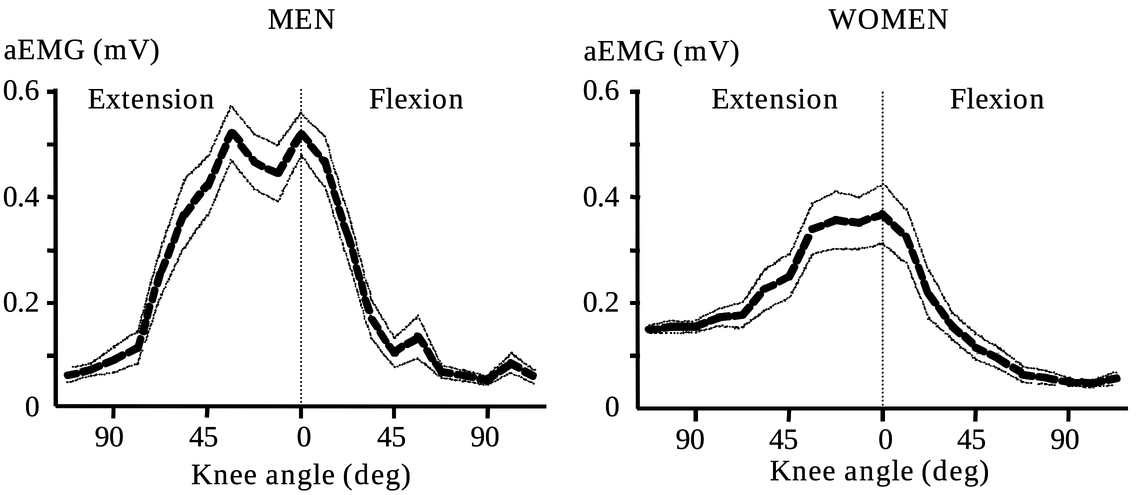

FIGURE 12 Mean (± SE_M) aEMG patterns of the hamstrings during repeated barefoot knee extension-flexion in men and women

The angular velocity patterns of the single trial extension and flexion in women are shown in Figure 13. The mean peak angular velocity of the single extension effort was 470 ± 64 deg·s^{-1} in the males and 480 ± 69 deg·s^{-1} in the females. In the single flexion effort, the mean of the peak velocity was 470 ± 78 deg·s^{-1} in the males and 375 ± 68 deg·s^{-1} in the females.

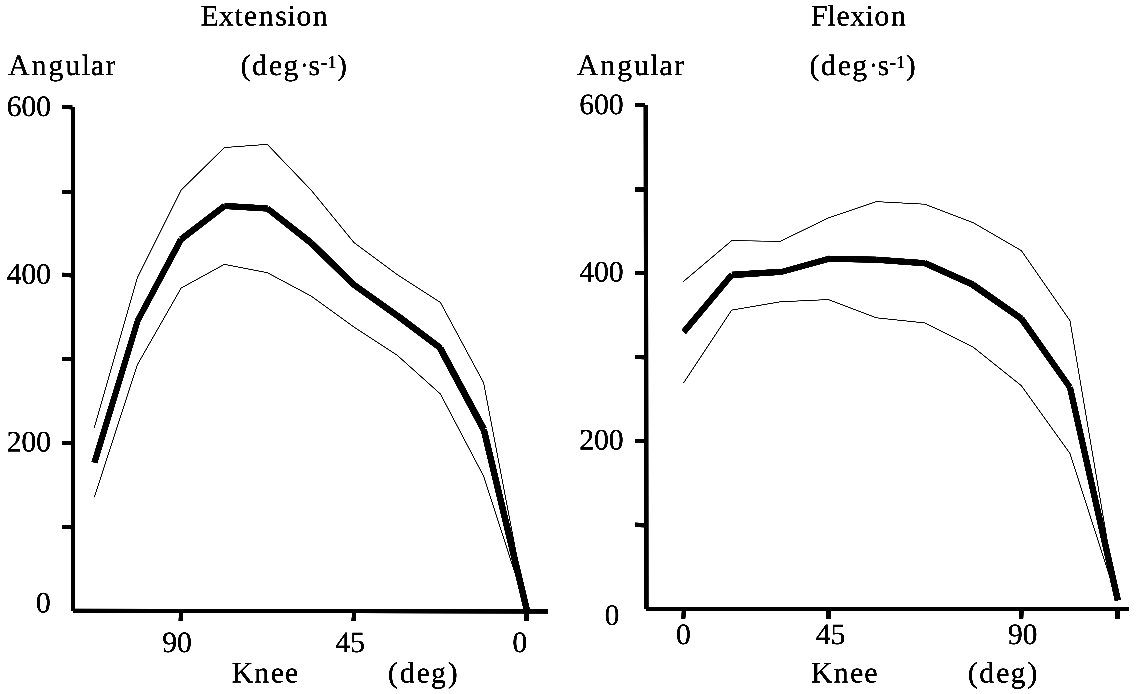

FIGURE 13 Mean (± SD) angular velocity during barefoot single trial extension and flexion in women

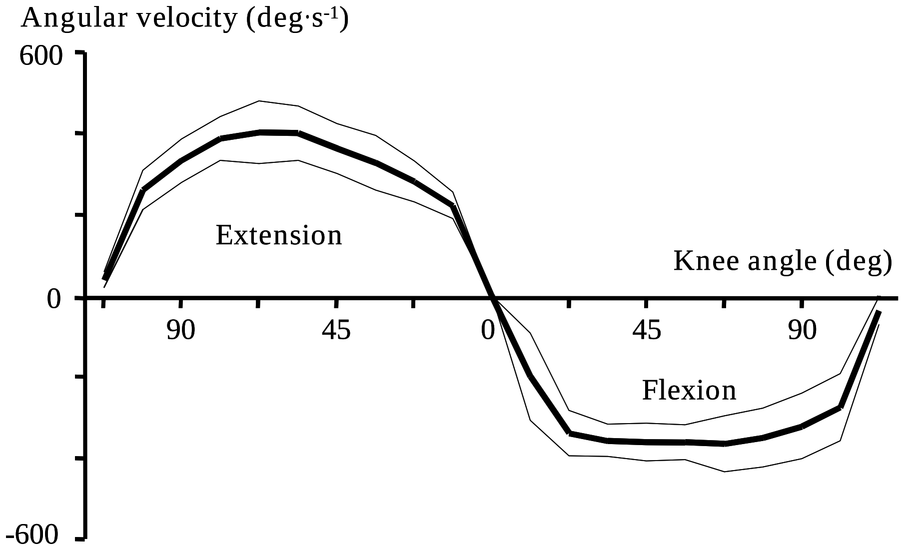

FIGURE 14 Mean (± SD) angular velocity during repeated extension-flexion in women.

In the repeated extension-flexion movement, as shown for women in Figure 14, the means of the peak velocities of 473 ± 110 and 458 ± 81 deg·s^{-1} were obtained in men and women, respectively. In the flexion phase, the mean peak angular velocity was 390 ± 40 deg·s^{-1} in the males and 364 ± 68 deg·s^{-1} in the females. In addition, the curves during the single and repeated flexion efforts showed a fairly constant velocity for the major part of the ROM (Fig. 14).

When comparing the angular velocities between barefoot and hydro-boot conditions during the repeated extension-flexion, the means of the angular velocities in the barefoot condition were higher ($p<0.001$) than with the hydro-boot. The males produced higher ($p<0.01$) velocities in the barefoot condition than the females during extension (364 ± 120 vs. 302 ± 110 deg·s^{-1}) and during flexion (326 ± 30 vs. 296 ± 33 deg·s^{-1}). With the hydro-boot, the means of the angular velocities for the males were higher ($p<0.05$) compared to the females during extension (210 ± 73 vs. 193 ± 72 deg·s^{-1}) The mean angular velocity in flexion did not differ (174 ± 54 vs. 168 ± 62 deg·s^{-1}) between the genders.

5.3.2 EMG activity and resistive forces in water and on land

The EMG patterns of the quadriceps and hamstrings were similar to the barefoot EMG patterns in both subject groups with the hydro-boot during repeated knee exercise. Small differences in the duration of the agonist/ antagonist activity patterns were observed as shown in Figures 15 and 16. The EMG bursts of the agonists (quadriceps, hamstrings) with the hydro-boot were elongated compared with the barefoot condition. Figure 17 shows the isokinetic force (left part) and related EMG curves (right part) of the male subjects. As shown in Figure 17 (right) the agonists were activated during major part of the

ROM in the isokinetic trials, whereas the activity of the antagonists remained low.

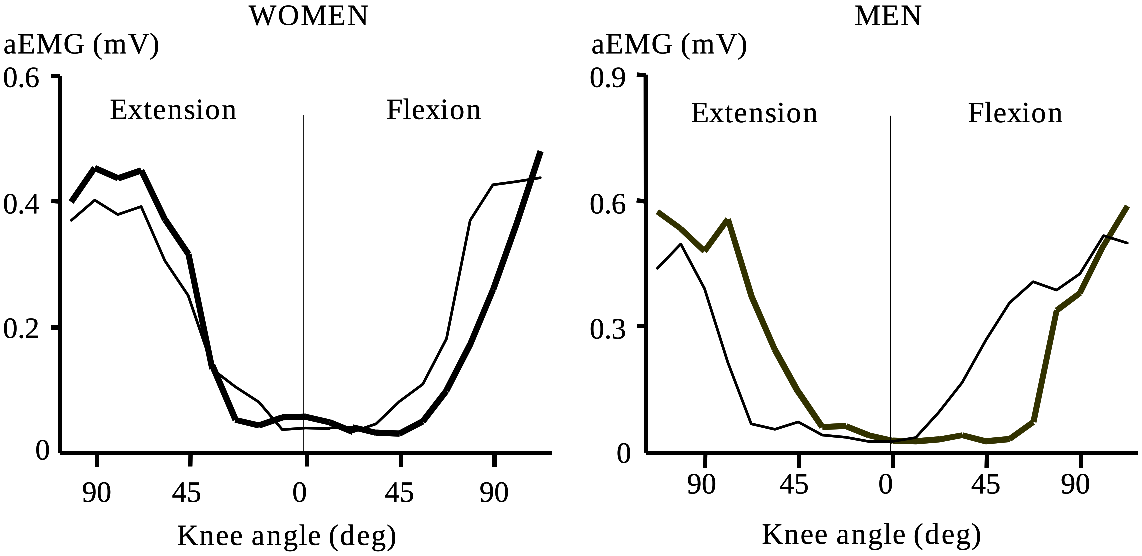

FIGURE 15 Mean aEMG activity patterns of the quadriceps during repeated knee extension-flexion underwater in barefoot (thin line) and with hydro-boot (thick line) in women and men

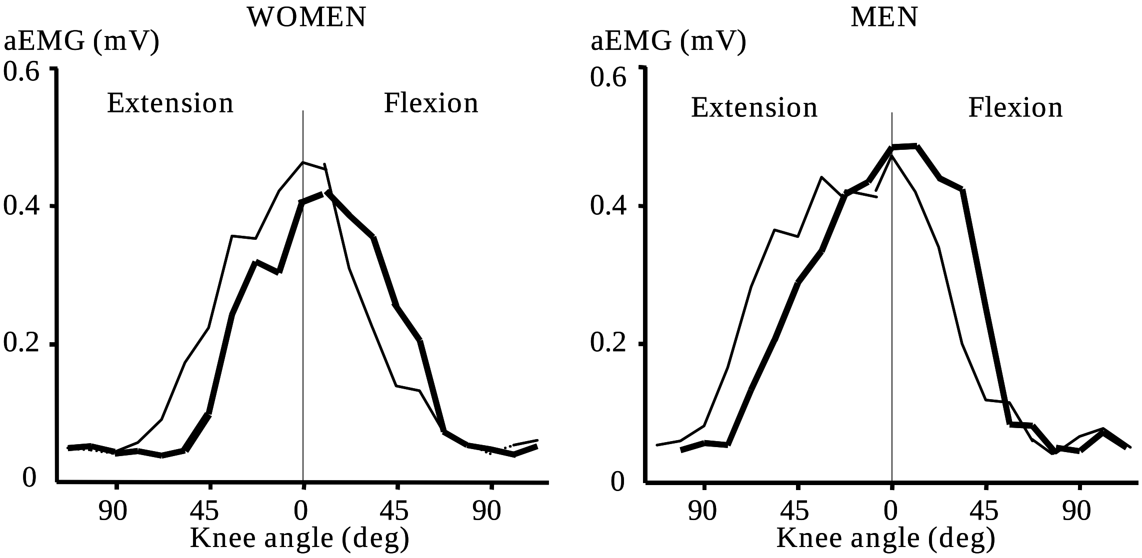

FIGURE 16 Mean aEMG activity patterns of the hamstrings during repeated knee extension-flexion underwater in barefoot (thin line) and with hydro-boot (thick line) in women and men

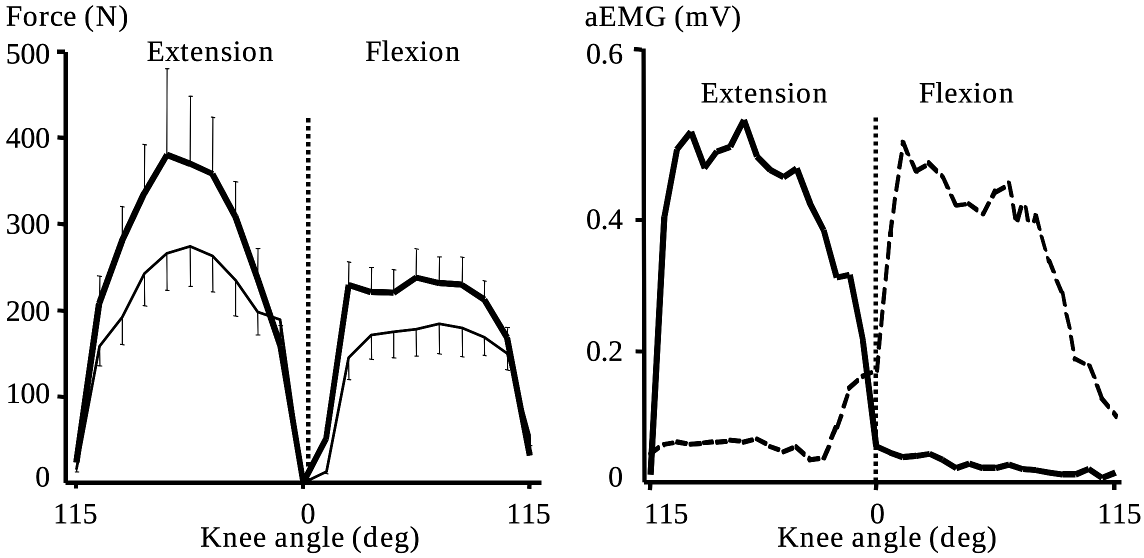

FIGURE 17 Mean (±SD) extension and flexion force curves in isokinetic condition (left) at the angular velocity of 180 deg·s^{-1} in men (thick line) and in women (thin line). The mean aEMG activity pattern of the quadriceps (solid line) and hamstrings (dashed line) during isokinetic knee extension-flexion at the angular velocity of 180 deg·s^{-1} in men (right).

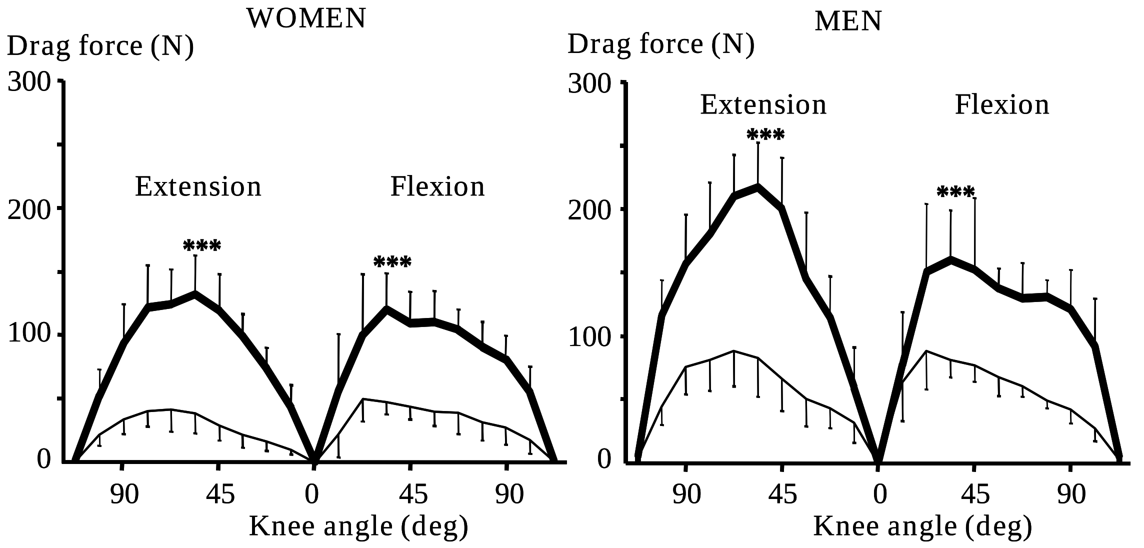

FIGURE 18 Mean (±SD) drag force curves of the barefoot (thin line) and hydro- boot (thick line) during extension-flexion in males and females. The asterisks indicate that the maximal drag forces differed significantly between these two conditions in the both subject groups (***, p < 0.001).

Figure 18 illustrates the drag force patterns underwater which show similarity to the extension-flexion force patterns in isokinetic measurements (see Fig. 17, right side). During the extension phase in Figure 18, the subjects reached the maximal drag force values at a knee flexion angle of 70° in the barefoot condition, and at a knee flexion angle of 60° with the hydro-boot. The means of the maximal drag force values in extension were greater ($p<0.001$) with the hydro-boot (209 ± 46 N in men, 145 ± 30 N in women) as compared to the barefoot condition (89 ± 34 N in men, 45 ± 15 N in women). The respective values in flexion were 176 ± 50 N for the males, 137 ± 26 N for the females with the hydro-boot, and 98 ± 30 N for the males and 55 ± 13 N for the females ($p<0.001$) in the barefoot condition. During the flexion phase, the maximal drag force occurred at 40 degrees of knee flexion in both underwater conditions (Fig. 18).

As shown in Figure 19, a comparison of the maximal extension-flexion forces between the land and water conditions indicates that the isometric forces (at 90° of knee flexion) in males and females were higher ($p<0.001$) than the maximal forces produced in the isokinetic and underwater exercises. Furthermore, the isokinetic forces at the angular velocity of 180 $\text{deg}\cdot\text{s}^{-1}$ were higher ($p<0.001$) than the underwater drag forces during the extension phase. The peak flexion forces in the isokinetic trials and with the hydro-boot did not differ from each other in either subject groups.

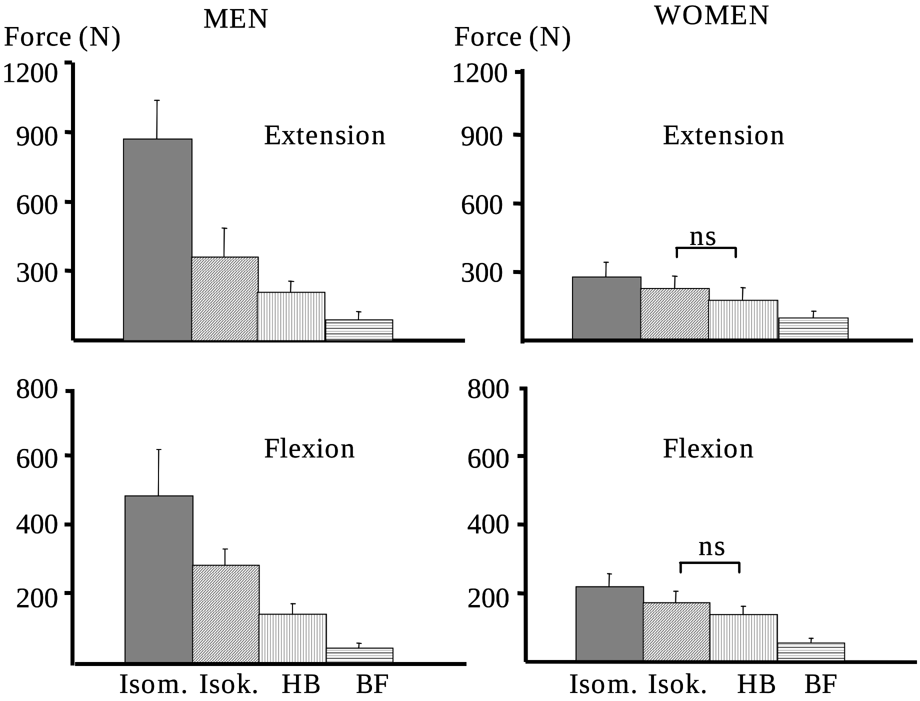

FIGURE 19 Mean (±SD) forces in the isometric and isokinetic conditions on land, and the drag forces determined in the barefoot and hydro-boot conditions in water. All conditions differed from each other ($p < 0.05$ – $p < 0.001$) except for the peak flexion forces between the isokinetic and hydro-boot conditions (marked non significant (ns.) in the figure). (Isom. = isometric, Isok.. = isokinetic, HB = hydro-boot, BF = barefoot)

5.4 Effects of aquatic training on neuromuscular performance

There were no significant differences between the exercise group and the control group in terms of age, stature and body mass. In the baseline measurements, no significant differences existed between the study groups in muscle torque, EMG values, LCSA or mean density of LCSA. The exercise group trained, on average, 24.8 times (22-26) during the 10 week training period. One subject had to withdraw from the training group after two weeks because of an acute respiratory infection. In addition, one other subject was excluded from the control group due to a increase in the level of physical activity from 2-3 times a week (baseline) to 7-8 times a week, as reported in the subject's exercise diary. Significant interactions of group by time were observed in each main outcome variable as seen in Figures, 20, 21 and 22. The ANOVA significance for group, time and interaction are shown in the figure-legends.

5.4.1 Effects on isometric torque

The aquatic training improved the isometric torque of the knee extensors and flexors of the subjects in the exercise group compared to the control group subjects. The individual percentage changes in the isometric torques are shown in Figure 20.

No changes were observed in the exercise group after 5 weeks of training in the maximal isometric knee extensor and flexor torque values. However, the maximal isometric torque improved significantly (p= 0.01-0.001) between the 5- and 10-week measurements. The knee extension and flexion force-time curves both showed that the exercise group subjects significantly (p = 0.025) improved their force production during the first 150 ms after 5 weeks of training compared with the baseline measurements. During 200-500 ms interval of the force-time curves, no differences were found between the baseline and 5 week measurements.

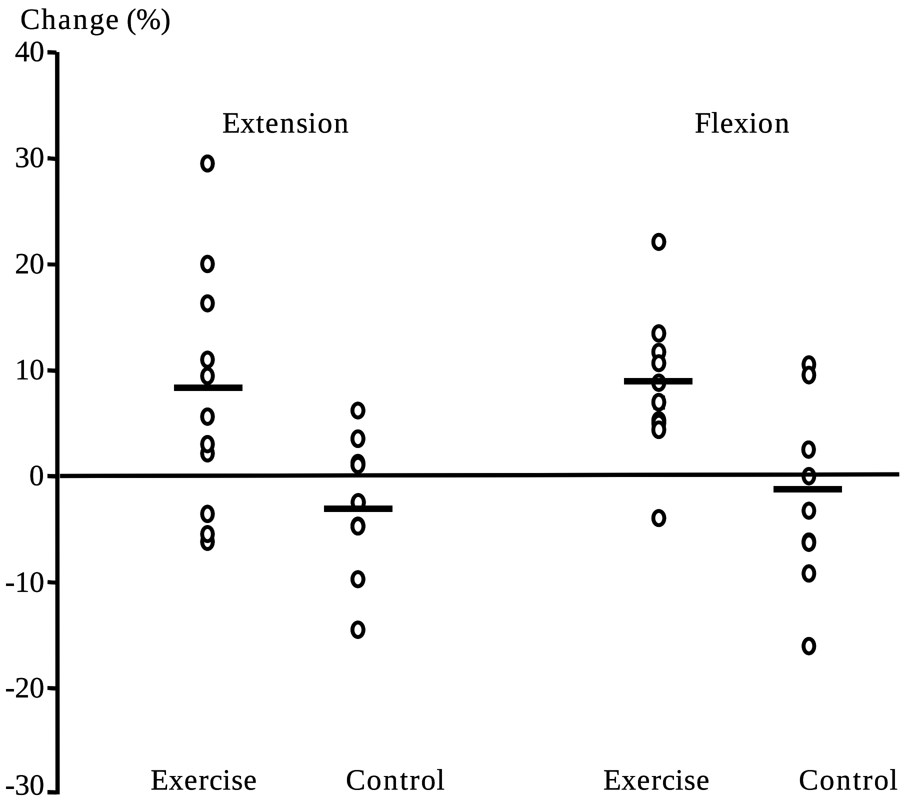

FIGURE 20 Individual percentage changes in isometric torque during knee extension and flexion in the exercise and control groups. The repeated ANOVA significances (p-values) for group, time and interaction were 0.669, 0.374 and 0.020 in extension, and 0.399, 0.078 and 0.008 in flexion, respectively. (— indicates means)

5.4.2 Effects on isokinetic torque

The isokinetic torque of the quadriceps and hamstrings of the subjects in the exercise group increased significantly compared to the control subjects. In isokinetic torque at 60 deg·s^{-1} the repeated ANOVA significances (p-values) for group, time and interaction were 0.569, 0.327 and 0.001 in extension, and 0.263, 0.121 and 0.009 in flexion, respectively. The individual percentage changes in the isokinetic torques measured at 180 deg·s^{-1}are shown in Figure 20.

The results of the measurements of the exercise group at the baseline and at 5 weeks showed no differences in the maximal isokinetic torque of the knee extensors and flexors. The isokinetic torques improved significantly (p= 0.05-0.001) between the 5 and 10 week measurements.

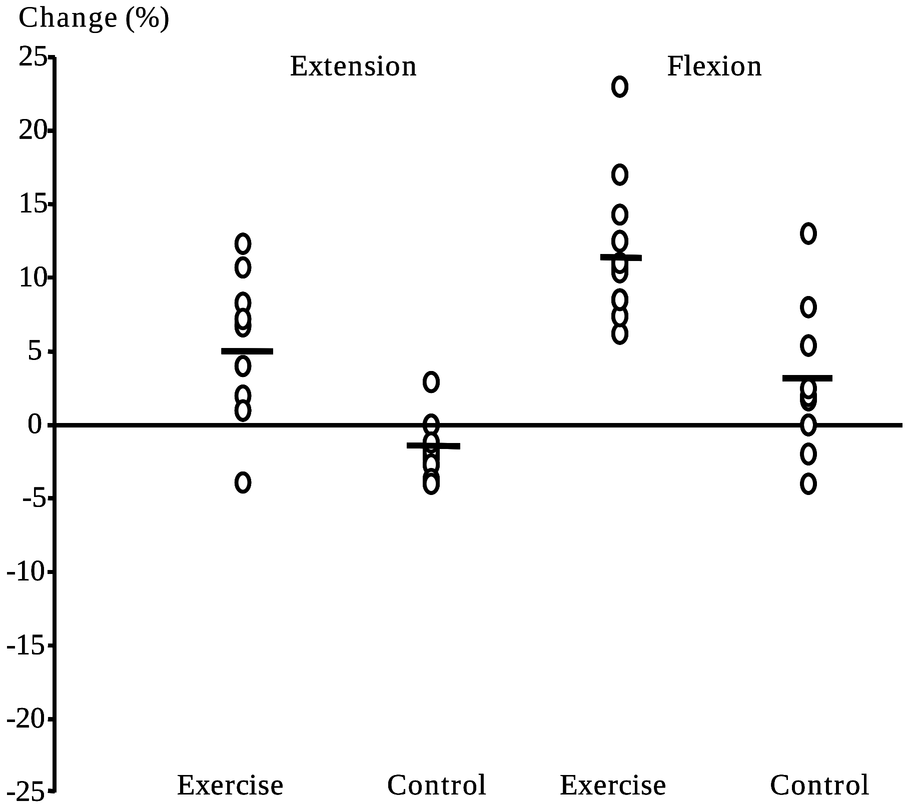

FIGURE 21 Individual percentage changes in isokinetic torque (180 deg·s^{-1}) during extension and flexion in the exercise and control groups. The repeated ANOVA significances (p- values) for group, time and interaction were 0.465, 0.460 and 0.001 in extension, and 0.279, 0.012 and 0.001 in flexion, respectively. (— indicates means)

5.4.3 Effects on muscle activity

Aquatic training improved the EMGs of the maximal isometric extension and flexion efforts by 26.4% ($p = 0.022$) and 10.0% ($p = 0.042$), while the changes in the control group were –1.0 and –2.1%, respectively. In the exercise group, the mean changes in the EMGs of the quadriceps during peak isokinetic torque production ranged from 19.2 to 27.7% ($p = 0.002$-0.01), and from 10.2 to 19.9 % ($p = 0.005$-0.05) for the hamstrings. In the control group, the respective changes in the EMG activities during isokinetic efforts were from –1.8 to +6.5% in quadriceps and from –0.4 to –8.9% in hamstrings. The control group did not show significant changes in EMG activities between baseline and 10 week measurements.

The results of the measurements of the exercise group at the baseline and at 5 weeks showed no differences in the muscle activities of maximal isometric and isokinetic knee extension and flexion efforts. The EMGs improved significantly ($p= 0.01$-0.001) between the 5 and 10 week measurements.

5.4.4 Effects on muscle mass (LCSA)

After 10 weeks of aquatic training, the LCSA the quadriceps and hamstring muscles of the subjects in the exercise group increased significantly compared to control group subjects. Figure 22 shows the individual percentage changes of the LCSA.

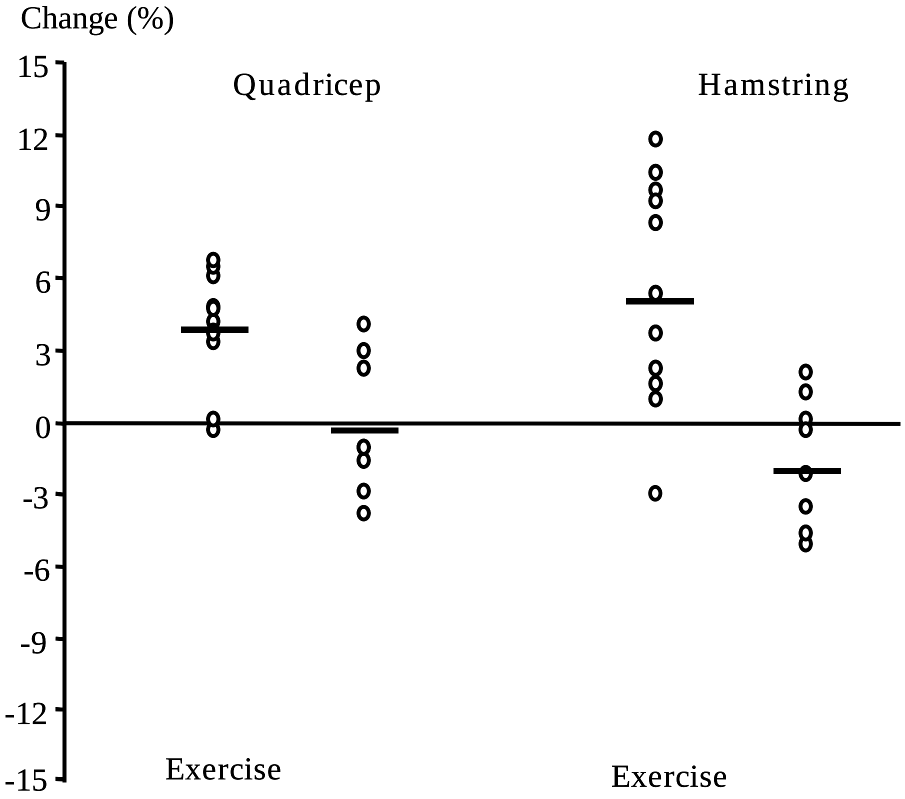

FIGURE 22 Individual percentage changes in the LCSA of the quadriceps and hamstring muscles in the exercise and control groups. The repeated ANOVA significances (p-values) for group, time, interaction were 0.417, 0.050 and 0.020 in quadriceps, and 0.758, 0.684 and 0.009 in hamstrings, respectively. (— indicates means)

6 DISCUSSION

The main findings indicated that the water condition, that is, the state of partial weightlessness and hydrostatic pressure, seems to have unique effects on neuromuscular function during isometric action and dynamic movements compared to dry land conditions. By considering the interrelationships between water, a moving object, and basic biomechanical principles, an aquatic environment seems to offer an effective, alternative medium for exercise for therapeutic or conditioning purposes. More specifically, the results showed acceptable reproducibility of isometric force and EMG measurements both in water and on land. The EMG activity of the measured muscles and the EMG/force ratio underwater showed lower values than when measured on land. A similar trend was observed in the reflex responses. The still and flowing water conditions had specific effects on muscle function, especially as shown in the repeated knee extension-flexion movements, in which the EMG patterns demonstrated an early decrease in the concentric activity of the agonists with coincidental activation of the antagonists. When using the resistance boots, the calculated drag forces reached peak values of 209 ± 46 N in men and 145 ± 30 N in women during knee extension. Finally, the results showed that, in healthy women, 10 weeks of progressive aquatic resistance training significantly improved neuromuscular performance with a significant gain in the LCSA of the knee extensor and flexor muscles.

6.1 Reproducibility of EMG and isometric force measurements

The reproducibility coefficients (ICC) of the EMG and isometric force measurements were found to be similar in water and on land, and they ranged between 0.85 and 0.98. There are no universally accepted values for ICC, but some authors (e.g. Baumgartner 1989) have suggested that an ICC greater than 0.80 presents a good level of repeatability, whereas categories ranging from questionable (0.70 to 0.80) to high (>0.90) are provided by Vincent (1994). According to the published literature, the reproducibility coefficients of isometric knee extension force on dry land have seemed to be acceptable (e.g. Viitasalo et al. 1980, Bemben et al. 1992, Christ et al. 1994). In EMG reproducibility studies of isometric knee extension, Viitasalo and Komi (1975) have reported within-day values of the Rectus Femoris muscle ranging from 0.77 to 0.92, and the day-to-day reproducibility ranging from 0.34 to 0.88. Viitasalo et al. (1980) reported high within-day reproducibility of the integrated EMG (iEMG) measurements (ICC = .98, CV = 6.9%) of isometric contractions of the Quadriceps muscle. According to Heinonen et al. (1994), the day-to-day reproducibility (ICC) of the knee extensors of sedentary women ranged from 0.30 to 0.70 and CV from 4.5 to 14.0%. Sleivert and Wenger (1994) reported day-to-day reproducibility values (ICC) of the iEMG of knee extensors ranging from 0.80 to 0.86. Howard and Enoka (1991) found that the trial-to-trial variability of the EMG of the vastus lateralis muscle between three maximal knee extensions is considerable, which may reflect inter-trial variations of neural drive, whereas the force output remained constant. The results of the present study were similar, with the trial-to-trial CV ranging from 6.0 to 7.5% for maximal torque output, while the CV for the EMG measurements ranged from 7.5 to 11.5%. The ICC addresses agreement in evaluating reproducibility because it is affected by systematic changes in the measurements. Intra-subject CV demonstrates more the precision of the measurements instead of the reproducibility, and therefore, it has been reported that CV can be used when comparing results with those of studies in this field (Knutson et al. 1994). However, it should be noted that comparisons between the different EMG studies are difficult to interpret because of differences in the statistical methods used.

6.2 EMG, isometric force and reflex sensitivity

While the maximal isometric force during knee extension remained relatively unchanged between the water and dry conditions, the EMGs of the knee extensors showed significantly decreased (11-18%) amplitudes during maximal and sub-maximal actions. The maximal force production of the plantarflexors decreased slightly more, by approximately 13 %. This reduction was not due to a difference in the activation level between the two conditions. This was revealed by the superimposed double twitch measurements, which were utilised in the MVC recordings of the plantarflexors. The related EMGs of the soleus and gastrocnemius muscles measured in water also decreased by approximately 30% compared to the respective values in the dry land condition. These findings of the plantarflexors support the results obtained from the measurements during knee extension. Therefore, water immersion significantly decreased the EMG/force ratio of the knee extensor and plantarflexor muscles. An impairment was also observed in the measurements of the H- and Achilles tendon reflexes. The present findings are in agreement with those of Clarys et al. (1985), who stated that despite varying the tapings and plastic protections on the electrodes, the detectable electrical output of human muscles was decreased in water. Fujisawa et al. (1998) also reported that the EMG activity of therapeutic shoulder exercises underwater was decreased during isometric contractions compared to identical measurements performed on dry land. Unfortunately, force production was not measured in the previous two studies.

The influence of electromechanical factors underwater on EMG signals seems to play a minor role when compared to the neurophysiological factors. Present findings indicated that water seems to have no effect on the attachment of electrodes as shown by the similarity between the before and after measurements of inter-electrode resistance. In addition, the reproducibility of the measurements underwater was similar to the measurements on land. This is also supported by the finding that no differences were found in the M-wave peak-to-peak amplitude between the wet and dry conditions. The observations that the decrease in EMG amplitude measured with indwelling electrodes showed a similarity to that obtained with surface electrodes, was in agreement with the previous findings. It is notable, however, that the recordings with indwelling electrodes were performed only in three subjects. The possible effect of skin temperature changes on measured parameters was assumed to be negligible between the two conditions. The skin temperature showed an average values of 0.35 ± 0.20°C lower in water. This value was in accordance with Nadel et al. (1974), who reported that a difference between average skin and water temperatures of 0.25-0.75°C during swimming.

From the neurophysiological point of view, the effects of underwater weightlessness on neuromuscular function, especially on the muscle spindles and proprioceptive mechanisms during maximal or submaximal voluntary contractions, are relatively unknown. However, in the measurements of postural control in and out of water, Dietz et al. (1996) found lower amplitudes of surface EMG underwater and a decline of the EMG amplitudes was observed in different levels of immersion. Studies of postural reactions in weightlessness during space-flights have indicated significantly reduced EMG amplitudes (e.g. Clement et al. 1985). During walking and running in simulated gravity conditions, Ferris et al. (2001) reported a 30% decrease in soleus EMGs, and also H-reflex responses were decreased compared to normal gravity conditions. In addition, Avela et al. (1994) reported that muscle spindle activity may be decreased during jumping in unexpected gravity conditions. Despite the low number of subjects taking part in the reflex measurements in Study II, the results for each subject indicated that immersion with the head out of water seems to cause an impairment of neuromuscular function. The results from the tendon tap and H-reflex measurements suggest that at least part of this impairment could be due to a reduced function of some reflex mechanisms. Dietz et al. (1989) suggested that reflex stabilisation of posture underwater may depend mainly on the activation of the pressure receptors in comparison to the importance of the vestibulospinal and muscle proprioceptive reflex mechanisms on dry land. Thus, impulses from the pressure receptors, which are distributed over the body, may converge with other reflex pathways in the spinal interneuronal circuits (Lundberg et al. 1987). Therefore, it could be suggested that, in the present experiment, a reduction in the reflex sensitivity could be due to a presynaptic inhibition that is induced by the pressure receptors at the Ia afferent terminals. Further, according to the reduced tendon reflexes, the possibility of γ-loop disfacilitation (reduced Ia afferent activity) of the α-motor neuron pool cannot be excluded. In addition, it was rather interesting that immersion with the head out of water reduced the EMG/force ratio indicating that some compensatory mechanisms for the force generating capacity of the muscle could have been activated. It has been shown that there is an interaction between increased Ca^{2+} metabolism and twitch characteristics such as PTT (e.g. Metzger et al. 1990). Therefore, it would be tempting to suggest that, in Study II, slightly increased PTT due to immersion might indicate the relative increase in Ca^{2+} metabolism., which could partly compensate for the loss of force. This may result in a reduced EMG/force ratio. One can not either disclose the possibility that neural activity during immersion could be affected by the enhanced parasympathetic function of the autonomic nervous system (Šcramek et al. 2000).

6.3 Drag forces and coefficients of the leg/foot model

Theoretically, when a limb or prosthesis moves through water at a constant velocity, the resistance produced is mostly due to the shape of the model and the physical as well as hydrodynamic properties of water. Therefore, the forces generated by the prosthesis should remain at the same level. However, during elliptical, rotational knee extension, the resistance is also a result of the movement against buoyant forces and can be expressed as the “angle of attack” of the prosthesis in relation to the buoyancy. This is clearly seen in Figure 9 in which the highest forces were measured in the early part of extension, which was followed by a constant decline of the curves during the ROM. The ROM from 140° to 90° was associated with the forces that opposed buoyancy, and after passing 90° of knee flexion, the assistance of the buoyant forces, and partly the lift forces, decreased the drag, especially when reaching full extension. In addition, the moving prosthesis accelerates and brings along the surrounding water masses, thus causing resistance at the beginning of the ROM. This additional amount of water is called the added mass (Klauck 1999).

The reason for the five times higher maximal drag force, and the rather small decline in force curves with the hydro-boot, is due to the increase in the frontal area, and particularly, the change in the shape of the prosthesis to square-plate form compared to the streamlined barefoot model. The drag coefficients with hydro-boot demonstrated clearly higher values than coefficients in barefoot. Therefore, water flow becomes more turbulent, and consequently, this pressure or form drag generated a large fluid resistance along with the increased masses of water to be accelerated, and these resulted in an increase in drag. Figure 9 also showed that, as expected, velocity has an influence on force production in water, which is in accordance with the principles of hydrodynamics.

The drag coefficient curves, as expected, demonstrated the highest values with the hydro-boot during the early part of the extension movement. In contrast to the forces, velocity seems to have a minimal influence on the drag coefficients, and this finding is in accordance with the results of previous studies (Berger et al. 1995). In addition, according to Berger et al. (1995), the length and the immersion depth of the model have lesser influences on the coefficients of drag. As expected, while observing the shape and amplitude of the flexion force curves and subsequent C_d curves, a similarity to the extension movement was found both in the barefoot and hydro-boot conditions.

A source of error in the present results obtained when using the dynamometer, and when compared to human subjects, may be the stiff ankle of the model fixed, which was set at 20° of plantar flexion. In humans, the angle of the ankle during the early part of knee extension is usually more than 20° of plantarflexion. Consequently, lengthening of the lever arm will result in an increase in force production. In swimming and during water exercises, the foot is a major contributor to drag (propulsion). Pressure measurements have revealed that, in swimming, the foot seems to create about 70% of the leg's hydrodynamic reaction (Vorontsov and Rumyantsev 2000). In addition, the surface material of the prosthesis may slightly affect the measured drag force and related C_d value by changing the surface drag. The present method which was presented by Scleihauf (1979) and Berger et al. (1995) was useful for the purposes of Study II and may be further applied to determine the hydrodynamic forces and coefficients for different body segments.

6.4 EMG and angular velocity in single and repeated knee exercises

The two different flow conditions have specific effects on muscle function in both subject groups, and these are illustrated in Figures 10, 11 and 12. During the initial phase of both extension and flexion in single and repeated trials, the angle in relation to buoyancy is large as the leg opposes the buoyant forces, and thereby, the resistance produced by the water increases, which is seen as early agonist EMG bursts. This is also in accordance with the force curves generated by the human leg model as explained earlier. At the beginning of the flexion movement, the orientation of the leg is perpendicular to the direction of the buoyancy, and so creates optimal resistance to movement. On the contrary, in the final ROM of extension and flexion, the role of the buoyant force is to assist the movements when the leg approaches the horizontal position.

During repeated knee exercises in particular, the water masses in motion seem to modify resistance during movements. In addition to the influence of buoyant forces in repeated and single knee exercises, the pressure drag induces a major part of the resistance. This drag is formed due to the difference between high pressure on the front side of the leg and low pressure on the rear of the leg. Increasing water masses at the front side cause a powerful separation of the streamlines along the boundary layer on the surface of the leg. (Roberson and Crowe 1985, Colwin 1992). Consequently, turbulent flow is formed behind the leg, and the rotation of vortexes form a cavity, which tends to suck the leg in the opposite direction. In addition, during the early part of the ROM in the repeated trial movements, the lower leg accelerates the surrounding water mass but simultaneously opposes the flow of water after the change in the direction of the movement, and thus, the “added mass concept” (Klauck 1999) increases the level of water resistance. Consequently, the early agonistic EMG bursts during the acceleration phase of the lower leg were observed in both the single and repeated exercises.

Furthermore, in the repeated trials at the point where agonistic activity was reduced, the mass of water was sufficiently accelerated to cause a decrease in the activity of this muscle group while the leg movement still continued with the flowing water as observed in the angular velocity curves (Fig. 13). Thus, the added mass as an assister to the movement can be used to explain the results (Klauck 1999). Simultaneously, it was also necessary to decelerate the moving leg and to resist the increasing buoyant forces, as well as to anticipate (pre-activation) the change in the direction of movement. This is indicated by the early and surprisingly high eccentric activity of the Hamstring and Quadriceps muscles when acting as antagonists. The hydro-boot exercises elongated the agonist activity compared to the barefoot exercises; this is clearly seen in Figures 15 and 16. The increased frontal area enhances the magnitudes of the pressure drag and water mass surrounding the leg, and this results in an increase in the total drag of the movement.

During the single trials, the activity of the antagonist muscle was surprisingly low, especially during the final 20 – 30 degrees of ROM, with a minimal braking effect of the leg movement being demonstrated, as was explained earlier. It might be suggested that when rotating the leg in still water, the pressure difference becomes greater between front and rear sides of the leg and this results in a greater level of resistance compared to the exercises performed against water, which had already been accelerated. For this reason, swimmers try to find still water to push against in order to gain resistance for propulsion (Counsilman 1969). Furthermore, the still water condition seems to smoothen the movement during the final ROM of the single trial exercise even though the buoyancy increasingly assists the movement. This may, in part, explain the longer activation during the ROM compared to the repeated trial exercises. The acceleration of the water masses may also be delayed, and therefore, the requirement for increasing the activation of the antagonists to break the leg motion is low or negligible compared to the repeated trial exercises. The relatively high level of agonist pre-activity, as shown in Figure 10, may suggest the muscular contraction against the mass of water, as well as the influence of the buoyancy, in order to initially accelerate the leg movement.

In the single trial exercises, the knee movements seemed to be purely concentric, and this can be seen from the low level of co-activation of the antagonists. On the contrary, in the maximal repeated knee extension-flexion, eccentric muscle action is followed by concentric muscle action, that is, a stretch-shortening cycle (SSC) type of exercise (Komi 1984), in which subsequent muscle actions have an influence on each other. With respect to the altered muscle activity patterns in the repeated exercises, when compared to the single trials, there may be some neurophysiological effects present. When measured underwater, the angular velocities of the movements are fairly high, reaching a maximum of 630 deg·s^{-1} during extension. Consequently, neural inhibitory mechanisms that prevent increases in angular velocity during underwater SSC movements could be a reason for the reduced agonistic activity, as well as for the increased antagonistic EMGs. The purpose of the proprioceptive reflex system, muscle spindles, and joint receptors is to obtain feedback from the muscles, joints and other tissues for the adjustment of neuromuscular function in response to irregular movements and conditions (Cavagna et al. 1977). However, the function of these mechanisms may be altered underwater (Dietz et al. 1989, 1996).

The patterns and peak angular velocities were similar in the single and repeated exercises. During each exercise, the maximal angular velocities in extension, which peaked at 630 deg·s^{-1}, were higher than during flexion. This may be due to the more powerful quadriceps muscles as compared to the hamstrings. In addition, the present starting position emphasises the assistance of buoyancy to the movements during the extension phase from 90° to 0° as compared to the flexion movement. While no reference values have previously been measured during respective exercises, even higher peak velocities of 850 deg·s^{-1} have been reported for knee extension during the breaststroke whip kick in swimming (Keskinen et al. 1980). Interestingly, the present results showed that the flexion angular velocity, in particular, was fairly constant in the main part of the single and repeated movements. This may indicate that muscle actions accommodate to the variable resistance offered by water. Nevertheless, a similarity in flexion angular velocities between the male and female participants was observed. One explanation may be that, despite the higher muscular force capacity of the male participants, they generally have a larger frontal area of the lower leg as compared to females. This in part increases water resistance along with the increased amount of the water masses to be accelerated thus decelerating the movement.

6.5 EMG activity and resistive forces in water and on land

The activity patterns during the barefoot and hydro-boot conditions should be carefully considered when the drag force curves and values are interpreted. Concentric EMG activity decreased with a simultaneous increase in antagonist muscle activity during the final ROM of extension and flexion, whereas the calculated drag, as shown in Figure 18, remained fairly high during the respective ROM. This is partly because of the movement of the leg, which continues to move along with the flow of water as a result of inertia and / or the transfer of momentum between segments (Nilsson et al. 1985). In water, therefore, the period when the agonist activity is low, but the calculated drag is still fairly high, can be expressed as the passive phase of the movement. In contrast to the EMG patterns measured underwater, the agonist muscles were activated during the major part of the ROM in the isokinetic condition as observed in the isokinetic EMG patterns in Figure 17, while antagonist activity was simultaneously low. These findings are explained by the nature of isokinetics, in which constant angular velocities produce accommodating resistances to the movements (Wilk 1990).

The EMG activities of the knee extensors and flexors were comparable between the two water conditions and the isokinetic trials. However, the hydro-boot, as well as the isokinetic efforts, produced significantly higher forces than the barefoot condition, as can be seen in Figure 19. Simultaneously, the mean angular velocities were significantly higher in the barefoot trials compared to the hydro-boot and isokinetic efforts. This phenomenon could be explained by the fact that the high levels of muscle activity and high speeds of movement are positively interrelated (Aagaard 2000), which suggests that although the number and/or firing rate of the active motor units increase, the force production decreases significantly. This indicated a reduced level of force exerted by the cross-bridges at the higher angular velocities (Enoka 1988). However, the comparisons between EMG activities should be made with caution because there is difference in nature between water and isokinetic exercises as explained in the previous paragraph. On the other hand, the similarity between both isokinetic and aquatic exercises is that no external gravity loads are applied to the extremity, each repetition should be performed with maximal effort, and velocity is the controlling factor for the resistance in the movements.

Muscle action (input) produces angular velocities (output) by which the drag force values were calculated using the general fluid equation. The equation is composed of several crucial factors such as velocity, area of the limb, and the drag coefficient (e.g. Alexander 1977). Therefore, the possible measurement errors caused by these factors may have a cumulative effect on the drag force values. As an example, while estimating forces in swimming from three dimensional kinematic data, Peyton and Bartlett (1995) reported drag coefficient and hand speed errors of 20 and 6 %, respectively. For these reasons, the comparisons between the calculated resistive forces in water and the forces measured by accurate dynamometers on dry land should be made with caution. It should also be noted that the creation of completely comparable dynamic muscle actions and exercises between dry and water conditions is difficult. In swimming, Olbrecht and Clarys (1983) performed EMG analysis to compare the front crawl arm actions between movements during actual swimming and during a simulation of the crawl movement with different dry land training methods. They found little similarity in EMGs between the dry and wet arm cycle executions.

In Study III, when the drag forces were measured using a prosthesis of an adult human leg and foot in a water tank with an isokinetic dynamometer, the measured drag force values were fairly comparable with the drag force calculations for humans in Study V, as shown in Figures 9 and 18, respectively. This might indicate a level of validity for the drag force estimations for the human subjects. In order to quantify these peak drag forces, they were expressed as a percentage of the maximal isometric torque measured at 90° of knee flexion on dry land. The values in the barefoot and with hydro-boot corresponded, on the average, to 10 to 30% of the isometric value, but in flexion, the peak drag force values were in the range of 25-30 to 65% of the isometric value. It should be noted that isometric force produced at a knee angle of 90° is not necessarily the highest force output of the quadriceps or hamstrings. The peak drag force of flexion with the hydro-boot reached a level of 80-85% of the isokinetic forces at an angular velocity of 180 $\mathrm{deg \cdot s^{-1}}$ in men and women. The higher drag force in flexion as compared to extension in relation to the dry land forces was explained in chapter 6.4, p. 58.

However, the use of several angular velocities in isokinetics would have been useful when comparing underwater barefoot movements at high velocities to those performed on the isokinetic dynamometer on land. It should also be noted that drag forces that are generated only with the “one-sized” hydro-boot are not necessarily the highest forces for each subject. Therefore, the frontal area of the external devices, and thus the level of resistance, could be easily changed to accommodate the needs and force levels of each individual. This would enable the determination of the optimal relationship between the velocity increments and the frontal area of the moving extremity for training and testing purposes

6.6 Effects of aquatic resistance training

In this study, the mean percentage changes of 5-13% in the isometric and isokinetic extension torques were smaller than the changes of 13-35% reported in dry land studies (Young et al.1983; Cureton et al. 1988; Häkkinen et al. 1995, 1996; Chilibec et al. 1998, Lemmer et al. 2000). The mean increase of 19-28% in the EMG of the knee extensors was comparable with the 19% increase reported by Häkkinen et al. (1995,1996) and the gain of 4% in the LCSA of the quadriceps was in line with the changes of 3-6% reported by Young et al (1983), Cureton et al. (1988) and Chilibec et al. (1998). With respect to the knee flexor muscles, the torque improved by 9-13% in this current study, and this was accompanied by a 10-19% increase in the EMGs and by a 6 % gain in the LCSA after training. Cureton et al. (1988) reported that the strength of the knee flexors increased by 24%, but no hypertrophy was observed after 16 weeks of strength training. Sipilä and Suominen (1995,1996) found no training effects on the isometric strength and muscle mass of the knee flexors in older women after 18 weeks of strength training.

The comparisons between the different strength training studies should be made with caution. It is notable that some of the reviewed studies did not use randomised controlled study designs. In addition, the results of the refereed studies showed relatively large ranges of percentage changes in the torque values. This may be due to the variety of training programs and measurement technique used. Test mode specificity was also observed and therefore, changes in muscle strength were greatest when measured during the muscle action and conditions used in training. In this study, torque was tested on land conditions instead of in water, and this may partly explain the lower percentage changes in the torque values obtained in our study compared to the respective changes on dry land. Finally, the majority of the previous studies have emphasised the group mean values while only few have paid attention to the individual changes. Our study shows that the variability in training response is quite large, which is in line with other studies reporting individual changes.

There is one dry land experiment in which the study design and results are somewhat comparable to that used in the present study (Higbie et al. 1996). They showed that 10 weeks of concentric isokinetic training in untrained women (age 18-35) resulted in an increase of 18% in the maximum unilateral torque of the knee extensors, which was accompanied by an improvement of 22 % in EMG activity and a 6% gain in the CSA of the Quadriceps obtained using magnetic resonance imaging. The training sessions of their study were conducted 3 days/wk for a total of 30 sessions in which the subjects performed three sets of 10 maximal knee extension-flexion repetitions at an angular velocity of 60 $deg \cdot s^{-1}$.

It is well established that the underlying mechanisms behind the increases in torque after the initial weeks of strength training are mostly attributed to adaptive changes in neural activation, and thereafter, due to muscular hypertrophy (Moritani and de Vries 1979; Sale et. al 1988). The rates of the changes in the EMG measurements increased rapidly in the early conditioning period and decreased during the later training period (Moritani and de Vries 1979). Conversely, in the present study, the EMG and torque outputs within the exercise group were unchanged when measured after five weeks of training. This suggests that the initial 5 weeks seemed to be mostly power-type strength training, which was supported by the significant increase in isometric force production during the initial 150 ms interval in the extension and flexion force-time curves. This indicates that due to the small frontal areas of the first two resistance boots, the drag produced by the water remained low as compared to large resistance boot. The subsequent mean peak angular velocities reached the relatively high values of 420 and 315 $deg \cdot s^{-1}$, respectively. Therefore, the velocity of the exercises during the early training was high enough to improve explosive torque, but not maximal torque output. It should, however, be noted, that the control croup was not measured after 5 week of training.

As is commonly expected, the movements in water are purely concentric. However, the EMG findings in Study IV demonstrated that a reduction of agonist activity occurred concurrently during the final ROM with eccentric activity of the antagonists in repeated knee extension-flexion. This is partly due to the flow patterns of water, deceleration of the moving leg and pre-activation before the change in the direction of the movement (see Studies IV and V). Therefore, underwater knee extension-flexion seems to be a stretch-shortening cycle (SSC) type of exercise in which the subsequent muscle actions have an influence on each other (Komi 1984). According to several studies, training with combined eccentric/concentric muscle actions seems to result in greater gains in strength and power (e.g. Colliander et al. 1990; Dudley et al. 1991; O´Hagan et al. 1995) and in muscle mass (Higbie 1996) than pure concentric training. In addition, aquatic exercises, which are typically non-weight bearing single joint movements, may partly explain the training induced changes. These “simple” exercises seem to result in earlier hypertrophy than training involving multi-joint exercises, which may need a longer period of initial neural adaptation, and thereby, delayed hypertrophy (Rutherford and Jones 1986, Chilibec et al. 1998).

The encouraging effects of aquatic training on the knee flexor muscles support the findings of the Studies III, IV and V. (See explanations in chapter 6.4, p. 58). The results of this study also suggest that the frontal area of the external devices, and thus the level of resistance, could be easily changed to accommodate the needs and force levels of each individual. This enables the determination of the optimal relationship between the velocity increments and the frontal area of the moving extremity for training purposes.

6.7 Clinical implications for aquatic exercise

In the design of the aquatic training and rehabilitation programs, progression is required, and by varying the starting position to optimally utilize the resistance produced by water, as well as by considering the flow conditions, the training effect can be focused over the full ROM. In addition, the relatively high resistance produced by the hydro-boot compared to the barefoot condition emphasises the benefits of using external devices in strength training exercises underwater. This is supported by the positive changes in neuromuscular performance and muscle mass after 10 weeks of aquatic training in healthy women. The hydro-boot used in this study enlarged the frontal area of the lower leg by 30-40%, and simultaneously changed the shape of the leg from being streamlined to a square-plate. Therefore, the size of the frontal area of the external device, and thus the level of resistance, should be easily able to be changed to accommodate for the needs of each individual.

The results of the present series of studies may offer important clinical applications. The forces generated by the prosthesis underwater could be utilised in the design of effective aquatic exercise programs and a well-fitted prosthesis for, for example, below-knee amputees. The present findings indicated decreased reflex sensitivity underwater and this might support the use of hydrotherapy as an adjunct in the rehabilitation process in neurological patients suffering from spasticity. Grigoriev et al. (1996) reported that the reduced effect of gravity impairs the stretch reflex by decreasing the hyperexcitability of the α- motoneuron pool, which in part reduces the degree of spasticity (Mayer 1997). Future studies should therefore clarify the mechanisms behind the impairment of neuromuscular function in water and to investigate the responses of aquatic therapy in patients affected by alterations in muscle tone. Also the possible effect of the parasympathetic nervous function on the neuromuscular function during water immersion should be studied.

The single trial knee extension and flexion against still water seems to be a relevant mode of aquatic rehabilitation when the goal of the exercise program is isolated muscle action for the effective training of the knee extensors and flexors. This is due to the fact that the level of antagonistic co-activation is low, whereas the level of agonistic muscle activity is at a higher level in the final phase of the extension and flexion ROM compared with the repeated exercises. According to the underwater EMG and angular velocity data, the repeated knee extension-flexion exercise used in this study was a natural movement in which the subsequent muscle actions influence each other and a relatively high angular velocity occurs during the ROM. The importance of the hamstrings as a stabiliser of the knee joint appears to increase at high angular velocities (Ghena 1991). The early reduction of concentric quadriceps activity, which occurred concurrently with a high level of co-activation of the hamstrings during the final 30-40 degrees of knee extension, may produce a posterior shear force on the tibia. This is meant to reduce strain on the anterior cruciate ligament (ACL). Therefore, the present kind of aquatic exercise might be beneficial in physical therapy programs following ACL surgery, because it is important to avoid large and excessive loading of the healing graft of the ACL during final extension (Grood et al. 1984; Henning et al. 1985, Beynnon et al. 1995, Fitzgerald 1987). In addition, according to knowledge of the isokinetic velocity spectrum for the testing and training of the knee, the contractile velocity of the barefoot knee extension-flexion underwater is either fast or functional (Wilk 1996). This indicates a decreased level of compressive forces on the joint, especially in the Patellofemoral joint of the knee. Single and repeated aquatic exercises of the Hamstring muscles at relatively high velocities may be beneficial in the early rehabilitation of knee disorders, and especially after Hamstring muscle injuries. It should be noted, however, that additional research, including calculations of joint and ligament forces during underwater knee extension-flexion, will add to the body of knowledge concerning therapeutic water exercises before further clinical implications of the present knee exercises are made.

7 PRIMARY FINDINGS AND CONCLUSIONS

The main findings and conclusions of the present series of studies can be summarised as follows:

1) The measurements of the isometric force and EMG activity of knee extensor muscles showed acceptable reproducibility both in water and on land. The decrease in EMG amplitudes in the water was marked in the maximal and sub-maximal contractions, while the force output showed relatively similar values between the two conditions. Water immersion also tended to impair neuromuscular function in the plantarflexor muscles. The decrease in maximal force output was 13%, while the corresponding EMGs of the plantarflexors decreased by approximately 30%. An impairment was also observed in the H- and Achilles tendon reflexes. According to these results from the measurements of the knee extensors and plantarflexors, it could be suggested that the impairment of the neuromuscular function may partly be of a reflex origin due to mechanisms related to hydrostatic pressure and the reduced gravity conditions underwater.

2) The forces generated by the leg and foot model and the related C_d values were dependent on the orientation of the prosthesis within the elliptical knee extension-flexion ROM in the barefoot and hydro-boot conditions. The highest values were shown during the early part of the extension movement at the larger knee angles when the model opposed the buoyancy. As expected, the forces and coefficients of drag showed higher values in the hydro-boot condition than in the barefoot condition. The present method of measuring the drag forces acting on the model by an isokinetic dynamometer was useful for the purposes of this study.

3) The EMG patterns showed that the two different water flow conditions had specific effects on neuromuscular function in both subject groups. During the repeated trials, the reduction of agonistic muscle (quadriceps/hamstrings) EMGs occurred with a surprisingly early

activation of the antagonists in both subject groups. On the contrary, in the single trial efforts, the level of antagonistic activity was low with prolonged activity of the agonist muscles during the whole ROM. The angular velocities showed similar values between the single and repeated exercises. Clinically, the single and repeated exercises may have specific implications, for example, in isolated muscular training (single), and in the rehabilitation of knee disorders (repeated).

4) As expected, the quantification of drag forces underwater showed that the hydro-boot increased the level of water resistance, but interestingly, the muscle activity patterns and amplitudes between the barefoot and hydro-boot conditions were fairly similar. However, water, as the mode of resistance to the movements, modified the EMG patterns in comparison with the respective patterns recorded in the isokinetic condition. The resistive forces on dry land were higher than underwater, but surprisingly, the peak drag in the flexion movement with the hydro-boot did not differ from the respective forces in the isokinetic trials. Finally, the hydrodynamic principles and the use of external devices should be carefully considered to ensure progressive training conditions.

5 Ten weeks of progressive resistance-type aquatic training in healthy women increased maximal isometric and isokinetic torque of the knee extensors and flexors. The torque gains were accompanied with a proportional improvement in neural activation and with significant increases in the lean muscle masses of the quadriceps and hamstring muscles. Thus, progressive resistance-type aquatic training seems to lead to both functional and structural adaptations in the healthy neuromuscular system. Consequently, aquatic exercises can be recommended for neuromuscular conditioning in healthy persons, and it may offer an effective training tool for those with a limited capacity for exercising on dry land.

YHTEENVETO

Vesiharjoittelua käytetään yhä enenevässä määrin kuntoilu- ja terveysliikuntamuotona sekä aktiivisen fysioterapian menetelmänä. Vedessä vallitseva osittainen painottomuus, korkea hydrostaattinen paine sekä veden aiheuttama vastus luovat harjoitteluympäristön erityisesti henkilöille, joille maalla tapahtuva harjoittelu on rajoittunutta tai kivuliasta. Huolimatta vesiliikunnan ja hydroterapian suosiosta, tieteellinen tutkimustyö, jolla selvitetään vedessä tapahtuvan harjoittelun perusteita on ollut erittäin vähäistä. Uintia sen sijaan on tutkittu vuosikymmenien ajan allasolosuhteisiin sovelletuilla biomekaanisilla ja fysiologisilla mittausmenetelmillä.

Tämän tutkimussarjan tarkoituksena oli selvittää vedessä tapahtuvan harjoittelun perusteita erityisesti hermolihasjärjestelmän toiminnan osalta sekä määrittää veden vastusvoimia harjoitteiden aikana. Tarkoitus oli myös tutkia 10 viikkoa kestävän vesiharjoittelun vaikutuksia polven ojentaja- ja koukistajalihasten voimantuottoon, lihasten sähköiseen aktiviteettiin (EMG) ja lihasmassaan. Tutkimussarjaan osallistuneet koehenkilöt olivat terveitä 25-35-vuotiaita naisia ja miehiä. Tutkittu tieto terveillä henkilöillä luo perustan tarkoituksenmukaisille sovellutuksille fysioterapiassa.

Tutkimussarjan ensimmäisessä vaiheessa vertailtiin polven ojentajalihasten EMG aktiivisuutta sekä polven isometristä ojennusvoimaa maa- ja vesiolosuhteissa sekä määritettiin mittausten toistettavuus eli reliabiliteetti. Tulokset osoittivat, että vedessä ja maalla toteutettujen EMG- ja voimamittausten toistettavuus on hyvä. EMG-aktiivisuuksien todettiin olevan vedessä merkitsevästi alempia verrattuna maalla mitattuihin arvoihin. Ojennusvoimissa ei kuitenkaan havaittu merkitseviä eroja maalla ja vedessä suoritettujen mittausten välillä. Lisäksi toteutettiin tutkimus, jossa verrattiin nilkan plantaarifleksoreiden isometristä voimantuottoa, pinta- ja lankaelektrodeilla mitattuja EMG-aktiivisuuksia sekä refleksivasteita (H- ja akillesjännerefleksi) maa- ja vesiolosuhteiden välillä. Tulokset tukivat edellisen tutkimuksen löydöksiä viitaten alentuneeseen EMG-aktiivisuuteen ja refleksivasteisiin vesiolosuhteissa. Syinä alentuneeseen hermolihasjärjestelmän toimintaan näyttävät olevan vedessä vallitseva osittainen painottomuus sekä veden hydrostaattinen paine.

Tutkimussarjan toisessa, kolmannessa ja neljännessä vaiheessa selvitettiin polven ojentaja- ja koukistajalihasten EMG- aktiivisuusmalleja ja mitattiin liikenopeuksia harjoitteiden aikana. Lisäksi määritettiin veden tuottamia vastusvoimia. Mittaukset suoritettiin yksittäisten ojennus- ja koukistusliikkeiden aikana, jolloin vedessä ei ollut virtauksia sekä toistosuoritusten aikana, jolloin jatkuva liike aiheutti vesimassojen eri suuntiin tapahtuvan virtauksen. Toistuvien polven ojennus- ja koukistusliikkeiden aikana havaittiin liikeradan alussa konsentrisen lihastyön aikana korkea EMG-aktiivisuus, joka liikeradan keskivaiheilla nopeasti väheni. Samanaikaisesti vastavaikuttajalihasten eksentrinen eli jarruttava lihastoiminta alkoi lisääntyä liikeradan loppuosalla. Tällöin kyseessä on luonnollinen venymis-lyhenemissyklin kaltainen liikesuoritus. Yksittäisten ojennus- ja koukistusliikkeiden aikana havaittiin agonistitilihasten konsentrinen toiminta koko liikeradalla, kun taas antagonistilihasten aktivoituminen oli vähäinen. Kliiniseltä kannalta toistosuoritukset ovat toiminnallisia harjoitteita, kun taas yksittäiset suoritukset saattavat tehokkaasti harjoittaa yksittäistä lihasryhmää koko liikeradalla.

Vastusvoimat, jotka kohdistuivat vesitankkiin asetettuun sääriproteesiin mitattiin isokineettisellä dynamometrillä polven ojennus- ja koukistusliikkeen aikana. Mittaukset suoritettiin ”paljaalla” proteesilla sekä proteesiin kiinnitettyä vastussaapasta käyttäen. Saatujen voima-arvojen perusteella laskettiin vastuskertoimet liikeradan eri nivelkulmille. Vastuskertoimia puolestaan käytettiin osana yleistä nestevakiota, jolla määritettiin veden vastusvoimia koehenkilöiden suorittamien polven ojennus-koukistusliikkeiden aikana. Yleinen nestevakio määrittää vastusvoimia veden tiheyden, raajan etuosan pinta-alan, liikenopeuden neliön ja vastuskertoimen tulona. Koehenkilöiden säären liikenopeudet määritettiin vedenalaisilla videokuvauksilla ja liikeanalyysillä. Tulokset osoittivat, että veden maksimaalinen vastusvoima oli miehillä 210 ± 46 N ja naisilla 145 ± 30 N käytettäessä vastussaappaita. Veden vastus oli lähes kolminkertainen verrattuna maksimaaliseen vastukseen, joka kohdistui paljaaseen jalkaan liikesuorituksen aikana. Vesiharjoitteiden rasittavuutta voidaan lisätä suurentamalla säären pinta-alaa ja muotoa sekä ottamalla huomioon liikkeiden suoritussuunta veden nosteeseen nähden.

Projektin viimeisessä vaiheessa 24 tervettä naista satunnaistettiin koe (n=12) ja kontrolliryhmään (n=12). Koeryhmä osallistui 10 viikkoa kestävään progressiiviseen voimatyyppiseen vesiharjoitteluun, jonka tarkoituksena oli lisätä polven ojentaja- ja koukistajalihasten suorituskykyä. Veden vastusta lisättiin erikokoisten vastuskenkien avulla. Tutkimuksessa havaittiin, että vesiharjoittelun seurauksena polven ojentajien ja koukistajien isometrisesti ja isokineettisesti mitatut vääntövoimat lisääntyivät merkitsevästi (5-13 %) sekä samanaikaisesti mitatut EMG-aktiivisuudet lisääntyivät 19-27%. Polven ojentajien ja erityisesti koukistajien lihasmassa kasvoi 4-6% harjoittelun seurauksena.

Tutkimussarjan tulokset viittaavat siihen, että isometrisen lihastoiminnan aikana EMG-aktivisuus alenee vesiolosuhteissa verrattuna vastaaviin mittaustuloksiin maaolosuhteissa. Dynaamisten polviharjoitusten osalta tulokset osoittavat, että veden hydrodynaamisten olosuhteiden kuten virtausominaisuuksien ja nostevoimien sekä veden vastusta lisäävien laitteiden käyttö parantaa hermolihasjärjestelmän suorituskykyä. Lisäksi vesiharjoittelun seurauksena harjoitettavien lihasten massa kasvaa. Vedessä tapahtuvaa voimatyyppistä harjoittelua voidaan näin suositella sekä terveille että polven ongelmista kärsiville henkilöille.

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