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Anu Valtonen

Asymmetrical Muscle Strength Deficit, Mobility Limitation and Aquatic Resistance Training in Persons With Knee Osteoarthritis

JYVÄSKYLÄN YLIOPISTO

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Department of Health Sciences, University of Jyväskylä
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ABSTRACT

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The purpose of the study was to investigate the asymmetrical muscle deficit of the lower limbs, and its consequences for mobility limitation in 50-75-year-old persons with knee osteoarthritis (OA) and knee replacement. Also, the effects of aquatic resistance training on mobility limitation, muscle power, torque, cross-sectional area (CSA), and asymmetrical muscle deficit, and the maintenance of training-induced benefits were studied in persons with knee replacement.

Data from two research projects were used. KNEE-OA is a clinical randomized controlled trial (n=43) on the rehabilitation of patients suffering from end-stage OA of the knee joint. KNEE-REPLACEMENT is a clinical randomized controlled trial (n=50) on the effects of aquatic resistance training including patients recovering from knee replacement. Mobility limitation, muscle power, torque and muscle CSA were assessed, and the asymmetrical muscle deficit was calculated. Persons with knee replacement participated in 3-month aquatic resistance training intervention that aimed to improve lower limb muscle power and torque, and thus mobility. The maintenance of training-induced benefits was examined 12 months after cessation of training.

Persons with knee OA and knee replacement had substantial asymmetrical deficit in knee extensor and flexor power, torque and thigh CSA, from which asymmetrical muscle power deficit was associated with stair ascension. Progressive aquatic resistance training was feasible and effective for persons with knee replacement. Training decreased mobility limitation and asymmetrical muscle deficit. In addition, muscle power, torque and CSA increased by training. Training-induced benefits in muscle power were maintained at follow-up.

The results of the study indicate that large asymmetrical muscle deficits in lower limbs are present in persons with knee OA and knee replacement, and have effects on mobility limitation as well. In addition, aquatic resistance training offers an effective means to decrease mobility limitation by increasing muscle power, torque, muscle CSA and decreasing asymmetrical muscle deficit of the lower limbs. The results also suggest that training-induced benefits in muscle power may be maintained with regular physical activity alone.

Keywords: osteoarthritis, knee replacement, mobility limitation, asymmetrical muscle deficit, aquatic resistance training.

Author's address Anu Valtonen, MSc
Department of Health Sciences
University of Jyväskylä
P.O. Box 35
FI-40014 University of Jyväskylä, Finland

Rehabilitation and Pain Unit
Kymenlaakso Central Hospital
Kotkantie 41
FI-48210 Kotka, Finland

anu.m.valtonen@jyu.fi

Supervisors Professor Ari Heinonen, PhD
Department of Health Sciences
University of Jyväskylä
Jyväskylä, Finland

Professor Sarianna Sipilä, PhD
Gerontology Research Center and Department of Health Sciences
University of Jyväskylä
Jyväskylä, Finland

Exercise Physiologist Tapani Pöyhönen, PhD
Rehabilitation and Pain Unit
Kymenlaakso Central Hospital
Kotka, Finland

Reviewers Associate Professor Rana Hinman, PhD
Physiotherapy Department
University of Melbourne
Melbourne, Australia

Researcher Helena Gapeyeva, MD, PhD
Institute of Exercise Biology and Physiotherapy
University of Tartu
Tartu, Estonia

Opponent Adjunct Professor Jari Arokoski, MD, PhD
Institute of Clinical Medicine
University of Eastern Finland
Kuopio, Finland

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Vantaa, February 2013

Anu Valtonen

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, which are referred to by their Roman numerals. Additionally, some unpublished data are included in the thesis.

I Valtonen A, Pöyhönen T, Manninen M, Heinonen A, Sipilä S. Asymmetrical knee extensor power deficit slows stair ascension in patients with end-stage knee osteoarthritis: A cross-sectional study. Submitted for publication.

II Valtonen A, Pöyhönen T, Heinonen A, Sipilä S. 2009. Muscle deficits persist after unilateral knee replacement and have implications for rehabilitation. Phys Ther 89, 1072-1079.

III Valtonen A, Pöyhönen T, Sipilä S, Heinonen A. 2010. Effects of aquatic resistance training on mobility limitation and lower limb impairments after knee replacement (ISRCTN50731915). Arch Phys Med Rehabil 91, 833-839.

IV Valtonen A, Pöyhönen T, Sipilä S, Heinonen A. 2011. Maintenance of aquatic training-induced benefits in mobility and lower extremity muscles among persons with unilateral knee replacement. Arch Phys Med Rehabil 92, 1944-1950.

ABBREVIATIONS

95%CI	95% confidence interval
ANCOVA	Analysis of covariance
cm^2	Square centimeter; expression of muscle cross-sectional area
CSA	Cross-sectional area
CT	Computed tomography
$deg \cdot s^{-1}$	Degrees per second; expression of angular velocity
Contralateral knee	'Better knee', knee not awaiting knee replacement
OA knee	Knee with end-stage osteoarthritis awaiting knee replacement
HU	Hounsfeld unit; expression of muscle attenuation
K/L	Kellgren/ Lawrence osteoarthritis classification
KNEE-OA	Research project of women and men with end-stage knee osteoarthritis
KNEE-REPLACEMENT	Research project of women and men with knee replacement
$m \cdot s^{-1}$	Meters per second; expression of speed
n	Number
Nm	Newton meter; expression of muscle torque
Non-operated knee	'Healthy knee', knee without knee joint replacement
Operated knee	Knee with knee joint replacement
OA	Osteoarthritis
RCT	Randomized controlled trial
RPE	Rating of perceived exertion
SD	Standard deviation
TKA	Total knee arthroplasty
TKR	Total knee replacement
TUG	Timed up and go test
VAS	Visual analogue scale
W	Watt; expression of muscle power
WOMAC	Western Ontario and McMaster University Osteoarthritis Index

CONTENTS

1 INTRODUCTION

The proportion of older people is gradually increasing as many more of us are surviving into old age. As people are aging, the numbers of age-related diseases and injuries increase as well. Knee joint osteoarthritis (OA) is a progressive, degenerative joint disease, which is thought to result from biochemical changes and biomechanical stresses affecting articular cartilage. Aging is considered to be the most important risk factor for the progression of knee OA (Felson 2004).

Knee OA causes severe pain and stiffness in the knee joint (Haq et al. 2003, Das & Farooqi 2008), which results in the disuse of the painful limb and mobility limitation. Knee replacement is an end-stage surgical procedure that effectively and successfully relieves knee pain (NIH Consensus Panel 2004, Wylde et al. 2007, Nilsdotter et al. 2009b). After successful knee replacement surgery, mobility usually increases to the preoperative level within few months (Mizner et al. 2005a). However, this level is already severely impaired because of long-term disuse, and therefore, the mobility of the persons with knee replacement rarely reaches the level of the age-matched control subjects (Finch et al. 1998, Walsh et al. 1998, Mizner & Snyder-Mackler 2005, Noble et al. 2005, Wylde et al. 2007, Yoshida et al. 2008).

An important factor behind mobility limitation in knee OA, in addition to normal aging-related decrease, is the pain of the knee joint. Also, unilateral decreases in muscle strength and muscle mass are strongly related to mobility limitation (Barker et al. 2004, Liikavainio et al. 2008, Kauppila et al. 2009). Even after successful knee replacement surgery patients suffer from muscle impairments, which continue to persist for several months, even years after surgery (Huang et al. 1996, Walsh et al. 1998, Rossi et al. 2006, Meier et al. 2008), and have association with mobility limitation as well (Yoshida et al. 2008, Petterson et al. 2009). In addition to the impairments on the affected side, it is noteworthy that existing asymmetrical muscle deficit, that is side-to-side difference between the legs, may also explain problems in mobility. Previously, associations between asymmetrical muscle power deficit and mobility have been reported in healthy older women (Portegijs et al. 2005, Portegijs et al. 2006) and in women recovering from unilateral hip fracture (Portegijs et al. 2008).

However, it is not known whether the asymmetrical muscle deficit also explains mobility limitation in persons with unilateral knee OA and knee replacement.

As the number of persons with knee OA increases, and the mobility limitation and muscle impairments related to knee OA and knee replacement are substantial, the need to develop efficacious rehabilitation methods is obvious. Water is an example of an effective and pain-free training medium for persons with medical conditions that may restrict training on land. Previous randomized controlled trials (RCTs) have found positive effects in mobility or muscle strength after aquatic training in healthy adults (Petrick et al. 2001, Pöyhönen et al. 2002), in healthy older persons (Takeshima et al. 2002, Tsourlou et al. 2006, Katsura et al. 2010) and in persons with knee or hip OA (Foley et al. 2003, Cochrane et al. 2005, Fransen et al. 2007, Hinman et al. 2007, Wang et al. 2007, Wang et al. 2011). However, even though the aquatic training is clinically commonly used in rehabilitation after knee replacement, it is somewhat unclear whether aquatic resistance training is effective in decreasing mobility limitation after knee replacement (Harmer et al. 2009, Rahmann et al. 2009). In addition, the long-term effects of aquatic training are little studied (Harmer et al. 2009, Rahmann et al. 2009).

The present study was conducted to obtain knowledge about the asymmetrical muscle deficit, and its consequences for mobility in end-stage knee OA and after knee replacement. Additionally, the effects of aquatic resistance training on mobility limitation and muscle power, torque, CSA and asymmetrical muscle deficit after knee replacement and the maintenance of training-induced benefits were studied.

2 REVIEW OF THE LITERATURE

2.1 Knee osteoarthritis

Osteoarthritis (OA) is the most common joint disease in the world (Felson 2003). It is defined as a progressive, degenerative joint disease, which is the most common form of arthritis, especially in older persons. The disease is thought to result from biochemical changes and biomechanical stresses affecting articular cartilage (United States National Library of Medicine 2011). OA can occur in any synovial joint, however, knee and hip joints are the principal large joints affected by OA (Lawrence et al. 2008).

Pathophysiology
Articular cartilage consists of collagen fibrils and proteoglycan molecules, which comprise the articular matrix of chondrocytes, which are the cartilage producing cells, and water. OA causes degenerative changes in the cartilage, which can be divided into three phases. First, the superficial proteoglycan content decreases and the collagen fibrils break down, and thus, the water content increases. As a result the cartilage stiffness decreases (Buckwalter & Mankin 1998). Next, the synthesis of the cartilage matrix proteins increases. Also the destruction of the components of the extracellular matrix increases when the chondrocytes try to repair the damage. At this time, the cartilage stiffness may even increase further (Buckwalter 1995, Arokoski et al. 2000). Meanwhile, when the cartilage damage progresses, the calcified cartilage and subchondral bone become thicker due to the increased formation and resorption of the subchondral bone cells (Buckwalter 1995, Arokoski et al. 2000). In the third phase, the repair capability of the chondrocytes decreases, and the concentration of proteoglycans and the collagen fibrils decreases. Therefore, the splits of the cartilage extend down to the bone. When the cartilage is degenerated and the collagen network is broken, the cartilage cannot regenerate and therefore the change in cartilage is final (Arokoski et al. 2000). However, according to the theory by Radin et al. (1972) the progression of knee OA begins

by the loading of the joint, which causes microfractures to the subchondral bone and further leads to damage of the overloaded cartilage (Radin et al. 1972).

In addition to the cartilage damage, also the whole knee joint is affected by OA (Figure 1). The formation of osteophytes and subchondral cysts as well as the thickened joint capsule, episodic synovitis with increased production of cytokines, muscle weakness and atrophy are present in the pathogenesis of the knee OA (Buckwalter 1995, Buckwalter & Mankin 1998, Arokoski et al. 2000, Brandt et al. 2006). Even though the knee OA affects the entire joint, the impairment may also be unicompartmental, and medial compartment knee OA is more common than lateral compartment knee OA (Ackroyd 2003).

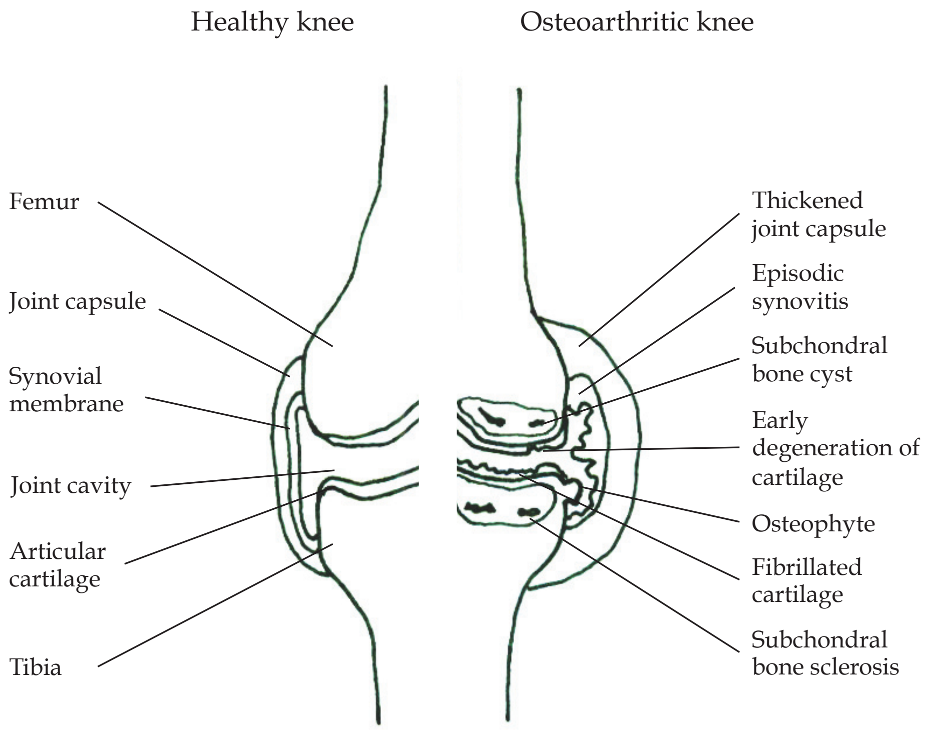

FIGURE 1 Healthy and osteoarthritic knee joint.

Risk factors

It is clear that aging is the most important risk factor for the progression of knee OA (Felson 2004). The prevalence of radiographic and symptomatic knee OA has been 4% in persons over 26 years old in the Framingham study (Felson et al. 1987), 17% in persons over 45 years old in the Johnston County study (Jordan et al. 2007), and 12% in persons over 60 years old in the NHANES III study (Dillon et al. 2006). Based on the Health 2000 examination survey in Finland, in women and men aged 55 to 64 years the prevalence of knee OA was 8% and 9%, and this showed a nonlinear increase to 18% and 11% in women and men aged 65 to 74 years (Arokoski et al. 2007).

Other systemic factors, such as female gender, genetic factors, geographic factors, race, obesity, diet and increased subchondral bone density can increase the risk for knee OA. Additionally, the local biomechanical factors such as earlier joint trauma, occupational knee-bending, high impact sports and muscle weakness are risk factors for knee OA (Arokoski et al. 2001, Haq et al. 2003, Felson 2004, Das & Farooqi 2008).

Symptoms, diagnosis and treatment

The dominant symptom in knee OA is the severe pain in the knee joint, which is related to the use of the joint and is usually relieved at rest. However, in severe knee OA the pain can appear also at rest and cause e.g. inability to sleep. Another important symptom in knee OA is the morning stiffness of the knee joint. Additionally, limited knee range of motion, crepitus, heat, effusion, instability, muscle weakness and atrophy are present in knee OA, which also affects mobility limitation and disability (O'Reilly & Doherty 2003).

Knee OA can be diagnosed with radiographic evaluation. There are many different classifications systems for assessing the severity of knee OA, but the most widely used classification system is the Kellgren/Lawrence (K/L) classification (Kellgren & Lawrence 1957), in which 0 refers to ´no OA´ and 4 to ‘severe OA´ (Table 1). Clinical diagnosis of knee OA is based on subjective symptoms e.g. pain, clinical findings e.g. malformation of the knee, decreased range of motion, case records and laboratory results. Also, the combination of radiographic and clinical classification criteria (Table 2) is widely recommended in the diagnosis of knee OA (Knee and hip osteoarthritis: Current Care guideline 2012).

TABLE 1 Severity of knee OA according to the Kellgren/Lawrence classification (Kellgren & Lawrence 1957).

Grade 1	Doubtful joint space narrowing and possible osteophyte lipping
Grade 2	Definite osteophytes and possible joint space narrowing
Grade 3	Moderate multiple osteophytes, definite joint space narrowing and some sclerosis and possible deformity of bone ends
Grade 4	Large osteophytes, marked joint space narrowing, severe sclerosis and definite deformity of bone ends

TABLE 2 Combination of clinical and radiological classification criteria in diagnosis of knee OA (Altman et al. 1986).

Knee pain on most days of prior month
AND
At least one of the following:
Age over 50 years
Morning stiffness less than 30 min in duration
Crepitus on active joint motion
AND
Osteophytes at joint margins (X-ray)

Currently, there is no cure for OA. However, the treatment of knee OA is comprised of weight reduction (Christensen et al. 2007), exercise (McKnight et al. 2010), patient education (Buszewicz et al. 2006, McKnight et al. 2010), manual and physical therapy (Knee and hip osteoarthritis: Current Care guideline 2012), use of assistive devices for walking and daily living (Moe et al. 2012, Simic et al. 2011), use of different medications (Zhang et al. 2010), and at the final stage, knee replacement surgery (Knee and hip osteoarthritis: Current Care guideline 2012). Knee replacement is a common end-stage surgical procedure that effectively relieves knee pain, and thus decreases mobility limitation in persons with knee OA (Martin et al. 1998, Orbell et al. 1998, NIH Consensus Panel 2004, Jones et al. 2005, Wylde et al. 2007, Nilsdotter et al. 2009a, Nilsdotter et al. 2009b). Knee replacement is defined as a replacement of the knee joint, where an artificial substitute for a body part (prosthesis) is inserted into tissue for functional purposes (United States National Library of Medicine 2011). The replacement of a knee joint can be total, whereby the whole knee joint is replaced, or partial, whereby only the medial or lateral part of the knee joint is replaced. In the literature the commonly used terms for knee replacement are total knee arthroplasty (TKA), total knee replacement (TKR) or partial knee replacement. Even though the knee replacement surgery effectively relieves pain, the osteoarthritis-related problems seem to have long-term problems for mobility (Walsh et al. 1998, Yoshida et al. 2008). Additionally, there are patients who also have pain, mobility limitation and disability after their knee replacement (Hawker 2006, Wylde et al. 2007). In addition, many patients are dissatisfied in their physical function after knee replacement even though they are satisfied with the decrease in pain (NIH Consensus Panel 2004, Wylde et al. 2007, Nilsdotter et al. 2009b).

2.2 Mobility limitation in persons with knee osteoarthritis

As described earlier, knee OA and knee replacement surgery affect mobility, which can be defined as a person's ability to move independently and safely from one place to another (Shumway-Cook & Woollacott 2007). Negative affects for mobility are called mobility limitation, which is a difficulty in walking from place to place. In the present study, mobility refers to walking and stair ascension. Further, the mobility limitation means difficulty in walking and in negotiating stairs.

There are many models that are used as a theoretical framework by researchers and clinicians to provide a common language for professionals and to help with focusing health care on the unique needs of the patient. The most widely used are the Nagi's disablement model, which was further extended by Verbrugge and Jette (Nagi 1965, Verbrugge & Jette 1994) and the World Health Organization's International Classification of Functioning and Health (ICF) (World Health Organization 2001, World Health Organization 2004). Both frameworks take into account the whole person and are based on the idea that all levels of the model should be considered in describing the dynamic process of the functional limitation by highlighting the patient-centered problems in daily life (Snyder et al. 2008, Jette 2009). Because of the terminology used in the model, the present study decided to use Nagi's disablement model (Figure 2) as a theoretical framework (Nagi 1965, Verbrugge & Jette 1994). According to the disablement process, the mobility limitation develops when the pathology or physiological abnormality, such as a disease or injury (e.g. knee OA), generates problems in the muscular system; the muscle impairments. Muscle impairment is a dysfunction or structural abnormality of the neuromuscular system. Muscle impairment (e.g. loss of muscle strength) may lead to functional limitation (e.g. slower walking speed) and finally to disability, which is the difficulty in doing activities of daily life, e.g. going shopping. In addition to the main pathway, the process is also affected by predisposing factors as lifestyle, demographic, social and behavioral factors. Also, intra-individual factors such as lifestyle and behavioral changes, psychosocial attributes and activity accommodations, and extra-individual factors such as medical care, rehabilitation, external supports and the environment may affect the process (Verbrugge & Jette 1994).

EXTRA-INDIVIDUAL FACTORS
MEDICAL CARE & REHABILITATION
(surgery, physical therapy, speech therapy, counseling, health education, job retraining, etc.)
MEDICATIONS & OTHER THERAPEUTIC REGIMENS
(drugs, recreational therapy/aquatic exercise, biofeedback/meditation, rest/energy conservation, etc.)
EXTERNAL SUPPORTS
(personal assistance, special equipment and devices, standby assistance/supervision, day care, respite care, meals-on-wheels, etc.)
BUILT, PHYSICAL & SOCIAL ENVIRONMENT
(structural modifications at job/home, access to buildings and to public transportation, improvement of air quality, reduction of noise and glare, health insurance & access to medical care, laws & regulations, employment discrimination, etc.

THE MAIN PATHWAY

PATHOLOGY → **IMPAIRMENTS** → **FUNCTIONAL LIMITATIONS** → **DISABILITY**

PATHOLOGY
(diagnoses of disease, injury, congenital/developmental condition)

IMPAIRMENTS
(dysfunctions and structural abnormalities in specific body systems: musculoskeletal, cardiovascular, neurological, etc.)

FUNCTIONAL LIMITATIONS
(restrictions in basic physical and mental actions: ambulate, reach, stoop, climb stairs, produce intelligible speech, see standard print, etc.)

DISABILITY
(difficulty doing activities of daily life: job, household management, personal care, hobbies, active recreation, clubs, socializing with friends and kin, childcare, errands, sleep, trips, etc.)

RISK FACTORS
(predisposing characteristics: demographic, social, lifestyle, behavioral, psychological, environmental, biological)

INTRA-INDIVIDUAL FACTORS
LIFESTYLE & BEHAVIOR CHANGES
(overt changes to alter disease activity and impact)
PSYCHOSOCIAL ATTRIBUTES & COPING
(positive affect, emotional vigor, prayer, locus of control, cognitive adaptation to one's situation, confidant, peer, support groups, etc.)
ACTIVITY ACCOMMODATIONS
(changes in kinds of activities, procedures for doing them, frequency or length of time doing them)

FIGURE 2 The disablement process (Verbrugge & Jette 1994).

2.2.1 Mobility limitation

Successful mobility requires numerous motor and sensory processes, which change with age and thus increase the mobility limitation as well. Therefore, it is known that maximal walking speed is affected by age (Bohannon 1997, Lauretani et al. 2003) whereas walking with habitual or comfortable speeds leads one to slow down to a smaller extent than walking with maximal speed (Cunningham et al. 1982, Bohannon 1997). However, negotiating stairs is a more complex and demanding mobility task than walking on a flat surface and can be even more affected by aging, diseases and injuries. When functioning on the upper limit of the performance, compensatory movement strategies are often needed (Hamel & Cavanagh 2004, Reeves et al. 2009). Older and mobility limited persons have been reported to use handrail-help or change their walking style from step over to two feet on same stair or even to sideways walking as compensatory movement strategies to complete the stair-ascension task (Hamel & Cavanagh 2004).

Studies conducted in persons with knee joint OA have shown that persons with knee OA have even more mobility limitation compared to age-matched people (Thomas et al. 2003, Piva et al. 2004, Liikavainio et al. 2008). For example, Liikavainio et al. (2008) reported from 16 to 20% lower values among persons with knee OA in 5 min walking distance, 20 m walking speed, lift repetitions and stair ascension and descension speeds compared to age-matched control subjects. In addition, persons with knee OA were slower in the timed up and go (TUG) test than healthy persons (Thomas et al. 2003, Piva et al. 2004, Liikavainio et al. 2008).

Even after successful knee replacement, patients suffer from mobility limitation, which can persist for several months after surgery. During the first month after knee replacement the mobility undergoes an expected decline compared to the preoperative values (Mizner et al. 2005a). Mizner et al. (2005a) reported, that performance in stair-climbing and TUG tests returned to the preoperative level at two months after surgery. Although functional ability may improve to the preoperative level, which most likely already is severely impaired because of pain and long-term disuse, it rarely reaches the level of age-matched control subjects (Finch et al. 1998, Walsh et al. 1998, Mizner & Snyder-Mackler 2005, Noble et al. 2005, Wylde et al. 2007, Yoshida et al. 2008). For example, people with knee replacements have been reported to have 17 to 18% lower maximal walking speed (Walsh et al. 1998, Yoshida et al. 2008) and they negotiate stairs even 43 to 51% more slowly (Walsh et al. 1998) than control subjects even beyond one year after surgery.

2.2.2 Factors associated with mobility limitation

Disuse-related decrease in muscle strength and cross-sectional area

For successful mobility, one of the most important prerequisities is sufficient lower limb muscle strength (Sakari-Rantala et al. 1998, Rantanen et al. 2001, Visser et al. 2005, Sakari et al. 2010, LaRoche et al. 2011). In persons with knee

OA, the mobility has been reported to be associated with muscle strength of the OA side and contralateral side (Gur & Cakin 2003, Barker et al. 2004, Liikavainio et al. 2008, Kauppila et al. 2009). For example, Liikavainio et al. (2008) found strong correlations between maximal walking speed, negotiating stairs and knee extensor-flexor muscle strengths among persons with knee OA. In addition to muscle torque, the lower leg power is known to be a just as important contributor for walking speed in healthy older persons (Bassey et al. 1992, Rantanen & Avela 1997, Bean et al. 2003, Bean et al. 2010). Muscle power is especially needed when performing more demanding functional tasks, such as stair ascension (Bassey 1997). In particular, the ability to recover from a stumble depends on the power and coordination of the leg muscles (Thelen et al. 1996, Robinovitch et al. 2000, Thelen et al. 2000). Therefore, muscle power has been suggested to be an even more important determinant of mobility than maximal force (Bean et al. 2002, Bean et al. 2003, Bean et al. 2010).

Comparisons between healthy persons and persons with knee OA reveal that muscle weaknesses and muscle atrophies in the knee extensor and flexor muscles are considerable in persons with knee OA (Berth et al. 2002, Lewek et al. 2004, Gapeyeva et al. 2007, Liikavainio et al. 2008, Petterson et al. 2011). Decreases from 20 to 48% in knee extensor torque (Berth et al. 2002, Lewek et al. 2004, Gapeyeva et al. 2007, Liikavainio et al. 2008, Petterson et al. 2011) and 13% in knee flexor torque (Liikavainio et al. 2008) have been found in persons with knee OA when compared to the healthy persons. However, the severity of the knee OA had no influence on the muscle strength (Liikavainio et al. 2008). In addition to the muscle weakness, persons with knee OA have been reported to have 12% smaller knee extensor muscle cross-sectional area (CSA) than healthy persons (Ikeda et al. 2005). On the contrary, by ultrasound measurements Liikavainio et al. (2008) found no decrease in knee extensor muscle mass compared to healthy persons.

Additionally, a few studies have shown that mobility limitation is associated with impairments in muscle strength and power also after knee replacement (Lamb & Frost 2003, Petterson et al. 2009). In the first month after knee replacement there is an expected decline in knee extensor muscle strength and muscle CSA, which slowly recovers during the next months (Berman et al. 1991, Perhonen et al. 1992, Rodgers et al. 1998, Rossi & Hasson 2004, Mizner et al. 2005a, Schroer et al. 2010, Petterson et al. 2011). However, knee extensor muscle strength is reported to remain 19% to 35% lower in people with knee replacement than in age-matched people even at 13 years after surgery (Huang et al. 1996, Walsh et al. 1998, Berth et al. 2002, Silva et al. 2003, Meier et al. 2008), and thus causes mobility limitations as well.

Asymmetrical muscle deficit

In severe OA of the weight-bearing joint the impairments of muscles on the affected side are mainly generated by unilateral pain-related disuse (Suetta et al. 2007). Therefore, it should be emphasized that in addition to the muscle weakness alone, the asymmetrical muscle deficit (muscle side-to-side difference between the legs) may independently lead to mobility limitation. However, the quantity of these studies is quite small. Previous studies with healthy persons have indicated mixed results about associations between asymmetrical muscle deficit and mobility (Portegijs et al. 2005, Portegijs et al. 2006, Carabello et al. 2010). Portegijs et al. (2005) indicated that asymmetrical knee extensor power deficit was associated with slower walking speed in healthy older women. In turn, Carabello et al. (2010) found no association between lower limb muscle asymmetrical deficit and mobility in healthy older persons. However, in clinical populations the asymmetrical lower limb power deficit has shown noteworthy effects on mobility, as in women recovering from unilateral hip fracture, greater asymmetrical power deficit was associated with slower stair climbing (Portegijs et al. 2008).

In most of the studies of participants with knee OA, decreases in muscle torque or power on the affected side have been reported (Robertson et al. 1998, Rodgers et al. 1998, Lorentzen et al. 1999, Anchuela et al. 2001, Berth et al. 2002, Lamb & Frost 2003, Mizner et al. 2005a, Rossi et al. 2006, Gapeyeva et al. 2007, Petterson et al. 2008, Schroer et al. 2010, Petterson et al. 2011, Barker et al. 2012). Muscle torque or power differences between the legs in different studies range from 7 to 32% in knee extensor muscles (Robertson et al. 1998, Rodgers et al. 1998, Lorentzen et al. 1999, Anchuela et al. 2001, Berth et al. 2002, Lamb & Frost 2003, Mizner et al. 2005a, Rossi et al. 2006, Gapeyeva et al. 2007, Petterson et al. 2008, Schroer et al. 2010, Petterson et al. 2011, Barker et al. 2012) and from 17 to 39% in knee flexors (Rodgers et al. 1998, Lorentzen et al. 1999, Rossi et al. 2006).

Three to six months after knee replacement surgery, muscle deficits of 21% to 42% in knee extensor torque and power of the operated side compared to the non-operated side have been reported (Berman et al. 1991, Rodgers et al. 1998, Lorentzen et al. 1999, Mizner et al. 2005a, Gapeyeva et al. 2007, Meier et al. 2008). Furthermore, knee extensor torque and power differences between the operated and non-operated side are maintained between 12 and 29% at least one to two years after surgery (Berman et al. 1991, Walsh et al. 1998, Anchuela et al. 2001, Mizner et al. 2005b, Rossi et al. 2006). Large muscle deficits between the operated and non-operated side have also been reported for knee flexor muscle strength after knee replacement (Walsh et al. 1998, Lorentzen et al. 1999, Rossi et al. 2006).

Only a few studies have investigated muscle CSA in persons with knee OA or knee replacement. However, in addition to muscle strength deficit, in persons with knee OA a unilateral disuse-related decline in muscle mass of the affected side when compared to the non-affected side exists (Petterson et al. 2008, Petterson et al. 2011). Deficits on the affected side in the knee extensor muscle CSA have been 12 to 15% in persons waiting for knee replacement because of knee joint OA (Petterson et al. 2008, Petterson et al. 2011). Large decreases in muscle CSA have also been reported after knee replacement surgery. Petterson et al. (2011) found 22% muscle CSA difference between the legs four weeks postsurgery, which declined to 15% in three months and to 7% one year postsurgery. However, studies conducted in persons with knee OA or knee replacement have not focused on individually calculated asymmetrical muscle deficit. Instead they have used group mean values to describe the decrease in muscle strength or CSA of the affected side. Therefore, it is not clear whether the asymmetrical muscle power, torque or CSA deficits in persons with knee OA and related knee replacement are associated with mobility limitation.

Pain

An important factor behind mobility limitation and disability in knee OA is the pain of the knee joint. For example, Kauppila et al. (2009) found that knee pain explained 41% of the variability in self-reported physical functional difficulty. High knee pain scores, and strong associations between knee pain and mobility limitation, have been found in several studies in persons with knee OA (Gur & Cakin 2003, Barker et al. 2004, Liikavainio et al. 2008, Kauppila et al. 2009, McDaniel et al. 2011). Also, muscle deficits in knee OA are suggested to result from severe pain at the impaired knee, which causes inability to fully activate the muscles (Fitzgerald et al. 2004, Lewek et al. 2004, Mizner et al. 2005c) and reflex inhibition (O'Reilly et al. 1997, O'Reilly et al. 1998, Hurley 1999). Severe knee pain leads to avoidance of activity (Holla et al. 2012), and in part, increases the disuse-related weakness and atrophy of the muscles (O'Reilly et al. 1997, Hurley 1999). However, successful knee replacement surgery usually decreases knee pain, and therefore it does not play important role in mobility postoperatively (Moffet et al. 2004, Escobar et al. 2007a, Escobar et al. 2007b, Bourne et al. 2010).

Other factors

In addition to adequate muscle strength and muscle mass, there are many other physiological factors, which are required for mobility. Insufficient postural balance (Lamb et al. 1995, Rantanen et al. 2001, Marsh et al. 2003, Tiedemann et al. 2005, Tiedemann et al. 2007, Sakari et al. 2010), increased reaction time (Tiedemann et al. 2005, Tiedemann et al. 2007, Sakari et al. 2010), decreased joint range of motion in the lower limbs (Beissner et al. 2000, Menz et al. 2005, van Dijk et al. 2009) and decreased physical fitness (Alexander et al. 2003, Malatesta et al. 2004, Morie et al. 2010) may cause mobility limitation. Also, impairment in sensory functions, such as vision, usually induces challenges for mobility (Sakari-Rantala et al. 1998, West et al. 2002, Tiedemann et al. 2005, Sakari et al. 2010). A variety of psychological factors underlying mobility limitations are cognitive problems, impairments in perception, as well as changes in attention, orientation and memory (Shumway-Cook & Woollacott 2007).

2.3 Aquatic training in decreasing mobility limitation after knee replacement

In the previous literature, there are not many randomized controlled trials (RCTs) which have investigated the effects of some form of land-based rehabilitation on muscle strength or mobility after knee replacement (Avramidis et al. 2003, Moffet et al. 2004, LaStayo et al. 2009, Petterson et al. 2009, Johnson et al. 2010, Kauppila et al. 2010, Avramidis et al. 2011, Russell et al. 2011, Stevens-Lapsley et al. 2012). Two of these studies used resistance training, which was compared with another type of resistance training, and resulted in no between-group differences (LaStayo et al. 2009, Petterson et al. 2009). However, when one study compared the resistance training cohort with the non-training cohort, the training positively affected muscle strength and mobility (Petterson et al. 2009). It might be that when the major problem, knee pain, is solved, the persons with knee replacement are considered as healthy. However, mobility limitation and asymmetrical muscle deficits can prevail even years after knee replacement (Huang et al. 1996, Walsh et al. 1998, Berth et al. 2002, Silva et al. 2003, Meier et al. 2008, Yoshida et al. 2008). Taking into account the harmful effects of asymmetrical power and torque deficits, individualized and targeted rehabilitation should be considered. Water might be an effective and comfortable training medium to conduct intensive resistance training after knee replacement.

2.3.1 Aquatic resistance training

In addition to land-based training, aquatic training is clinically commonly used in rehabilitation after musculoskeletal lower limb problems. Resistance training is defined as a type of muscle strength-building exercise program that requires the muscle to exert a force against some form of resistance, such as weight, stretch bands, water, or immovable objects (United States National Library of Medicine 2011). As mentioned in this definition, resistance training can also be conducted in a safe and comfortable training medium, water. Through the special properties of water the training can be easily individually adjusted for persons with medical conditions that may restrict training on land. Changes in the autonomic nervous and circulatory systems when in thermo-neutral water (34.5°C) increase blood flow to muscles and tissues to help the healing process, and the feeling of pain can also be modulated (Becker 2004). Additionally, the special properties of fluids offer many other advantages when performing exercises under water.

The hydrostatic pressure is the force produced by the water on an object submerged underwater. The hydrostatic pressure depends on the density and depth of a fluid, from which the density of water changes with temperature. In addition, the deeper the object is immersed, the more pressure exists on the object (Ohanian 1989). In rehabilitation, the hydrostatic pressure might be useful in decreasing effusion or allowing the patient to train without increasing effusion (Thein & Brody 2000). In general, hydrostatic pressure helps to reduce swelling in the joints and soft tissues, for example in the acute phase after knee or hip replacement (Rahmann et al. 2009) or in other conditions with lymphedema (Hartmann & Huch 2005, Tidhar et al. 2007).

When the body is immersed in water, it experiences an upward directed force, the buoyancy force. According to the Archimedes' Principle the buoyant force on an immersed body has the same magnitude as the weight of the fluid displaced by the body (Ohanian 1989). In aquatic training, buoyancy can be used as a support, assistance or resistance. Supported exercises are presented in a direction parallel to the bottom of the pool and assisted movements are performed upwards toward to the surface of water. However, if the buoyancy-supported or –assisted movements are performed at high speeds then the buoyancy can be overridden by viscosity and then the water resists the movement. Viscosity is the friction occurring between individual molecules in a liquid (Ohanian 1989). Viscosity resists the movement in water because liquid molecules adhere to the surface of the body (Thein & Brody 2000, Becker 2004). Water offers a predominance of concentric muscle contractions and thus decreases muscle damage after resistance training (Pantoja et al. 2009). During training the viscous resistance stops immediately after cessation of force because there is only a small amount of inertial moment. Hence, if the person feels pain during training the viscosity stops the movement almost immediately (Becker 2004). In addition to the viscosity resistance, also buoyancy can be used as a resistance. Buoyancy-resisted training is performed towards the bottom of the pool against the upward thrust of buoyancy (Thein & Brody 2000). In rehabilitation, when the person is submerged into the water, the buoyancy of the water assists to support the weight of the person. Hence, the buoyancy reduces the compressive and shear forces on weight-bearing joints (Triplett et al. 2009, Colado et al. 2010). When the stress of the joints is reduced, it is easier and less painful to train in water compared to dry-land training (Petrick et al. 2001, Wyatt et al. 2001, Gill et al. 2009).

The shape and size of the object affects the resistance in water. When an object moves under water it experiences drag force, which opposes the motion, and lift force, which exerts upward force on the object. When water moves around the object, there are two types of flow: laminar flow and turbulent flow. Laminar flow is the smooth flow of water molecules and turbulent flow is interrupted flow (Enoka 2002, Becker 2004). Turbulent flow produces the resistance, which is used in aquatic training (Thein & Brody 2000). Turbulence, and thus, the resistance can be increased during training by changing the shape of the object or by adding the surface area e.g. with resistance boots (Pöyhönen et al. 2001a, Becker 2004). Drag is the force that is caused by turbulence and viscosity of water. When an object moves through the water there is more pressure at the front of the object than at the back of the object, which is called the pressure drag. In addition, surface drag and wave resistance resist the movement of the object through the water. Training resistance increases by adding to the movement velocity in the water. This is because the resistance to movements offered by water increases with speed: the drag produced by water quadruples when the velocity doubles (Becker 2004). A lift force in water is created according to the Bernoulli's principle, where fluid pressure is inversely related to fluid velocity (Ohanian 1989, Enoka 2002). Lift force occurs in water when the object has an asymmetrical shape, when it is located at an angle relative to the fluid flow or when it is spinning. Lift force is generated because the velocity of the water flow is greater on the topside of the object and therefore the pressure on that side is smaller (Enoka 2002).

As described earlier, the water offers resistance to exercise movements. However, defining the optimal training intensity is a challenging task in water. The calculations of the size of the resistive equipment, length of the lever of a limb in motion, and the hydrodynamic position of the limb as well as its movement velocity can be performed before training (Pöyhönen et al. 2001a, Pöyhönen et al. 2001b). During training, the training load has been defined by objective heart rate monitoring (Taunton et al. 1996, Pöyhönen et al. 2001a, Takeshima et al. 2002, Tsourlou et al. 2006) or by subjective scales of perceived exertion e.g. Borg's Rating of Perceived Exertion (RPE) Scale (Wang et al. 2007, Colado et al. 2009b, Gill et al. 2009, Katsura et al. 2010, Wang et al. 2011). In addition, by controlling the pace of the movement the desired number of repetitions can be achieved during training (Petrick et al. 2001, Tsourlou et al. 2006, Colado et al. 2008, Lund et al. 2008, Colado et al. 2009a, Rahmann et al. 2009).

2.3.2 Aquatic training interventions to decrease mobility limitation

Aquatic training can be executed as different aquatic therapies, as endurance training, resistance training, several combinations and also in many other ways. However, this study focuses on aquatic resistance training with additional resistance (e.g. resistance boots, floaters, rings etc.) or without additional resistance (water only), with an intention to improve muscle power, torque, CSA and mobility.

Previously, RCTs studying aquatic training have been widely performed in healthy adults (Petrick et al. 2001, Pöyhönen et al. 2002, Colado et al. 2009a) and in healthy older persons (Takeshima et al. 2002, Tsourlou et al. 2006, Colado et al. 2009b, Katsura et al. 2010). From 8- to 24-week-long aquatic training programs have found to bring beneficial effects to lower limb muscle torque (Pöyhönen et al. 2002, Takeshima et al. 2002, Tsourlou et al. 2006), muscle power (Colado et al. 2009a) and muscle CSA (Pöyhönen et al. 2002), and also to the mobility of older persons (Tsourlou et al. 2006, Colado et al. 2009b, Katsura et al. 2010). For example, after 24 weeks of aquatic resistance training with additional resistance, Tsourlou et al. (2006) found a 19% training effect in TUG test compared to the non-training controls in healthy older persons.

Also in persons with knee OA, the number of earlier studies on aquatic training is quite large. Table 3 summarizes RCTs including aquatic training in persons with knee OA or knee replacement. In the knee OA RCTs comparing aquatic training with non-training controls, aquatic training has been conducted using additional resistance equipment (Foley et al. 2003, Cochrane et al. 2005, Silva et al. 2008) or without additional resistance (Fransen et al. 2007, Hinman et al. 2007, Wang et al. 2007, Lund et al. 2008, Lim et al. 2010, Wang et al. 2011, Hale et al. 2012). In most of the studies after aquatic training, the lower limb muscle strength increased (Foley et al. 2003, Hinman et al. 2007, Wang et al. 2007), mobility improved (Foley et al. 2003, Cochrane et al. 2005, Fransen et al.

2007, Hinman et al. 2007, Wang et al. 2007, Wang et al. 2011) and pain and self-reported functional difficulty decreased (Cochrane et al. 2005, Fransen et al. 2007, Hinman et al. 2007) compared to controls. For example, Wang et al. (2007) found 11% improvement in walking distance measured by a 6 min walking test, as the aquatic training group was compared to controls after 12-weeks of training.

Previously, RCTs have also compared aquatic training with land-based training in healthy adults (Petrick et al. 2001), in older persons (Taunton et al. 1996) and in persons with knee or hip OA (Wyatt et al. 2001, Foley et al. 2003, Lund et al. 2008, Silva et al. 2008, Gill et al. 2009, Wang et al. 2011). The interventions have been performed using additional resistance (Petrick et al. 2001, Foley et al. 2003, Silva et al. 2008) or without additional resistance (Taunton et al. 1996, Wyatt et al. 2001, Lund et al. 2008, Gill et al. 2009, Wang et al. 2011). No differences between the aquatic and land-based groups have been found in mobility (Wyatt et al. 2001, Silva et al. 2008, Gill et al. 2009, Wang et al. 2011) and muscle strength after training (Taunton et al. 1996, Petrick et al. 2001), or land-based training has been more successful in increasing mobility (Foley et al. 2003) and muscle strength (Foley et al. 2003, Lund et al. 2008) than aquatic training. However, after aquatic training the persons with knee OA have been less painful compared with land-based training (Wyatt et al. 2001, Bartels et al. 2007, Lund et al. 2008, Silva et al. 2008, Gill et al. 2009, Wang et al. 2011).

On the contrary, after knee replacement there exists very few RCTs that have studied the effects of aquatic training (Harmer et al. 2009, Rahmann et al. 2009, Liebs et al. 2012) (Table 3). One earlier RCT has compared aquatic rehabilitation without additional resistance and ward physiotherapy commencing four days after surgery. After two weeks of aquatic rehabilitation the researchers found positive results in lower limb muscle strength but not in mobility compared with the ward physiotherapy (Rahmann et al. 2009). Meanwhile, Liebs et al. (Liebs et al. 2012) compared 3-4 weeks of aquatic therapy without additional resistance starting either 6 days or 14 days after knee replacement and found no significant differences in self-reported functional difficulty at 3, 6, 12 and 24-month follow-ups (Liebs et al. 2012). Also, Harmer et al. (2009) compared land-based training and aquatic training without additional resistance and found no difference between the groups in terms of mobility or pain after a 6-week training period. However, these earlier interventions were short and used no additional resistance. Therefore, the knowledge of whether the persons with knee replacement can tolerate aquatic resistance training conducted with resistance equipment is sparse. Also, the training effects of progressive aquatic training interventions with additional resistance are not known.

The long-term effects of aquatic training have been examined in some studies only. In persons with knee replacement, three to six months after cessation of training the aquatic training group had improved their mobility compared to the land-trained group (Harmer et al. 2009), but another study showed that the training effect in muscle strength had disappeared compared to a ward physiotherapy group (Rahmann et al. 2009). In persons with OA, aquatic training-induced improvements may be at least partly maintained in mobility (Cochrane et al. 2005, Fransen et al. 2007, Hinman et al. 2007) or in muscle strength (Hinman et al. 2007) after six weeks to one year after cessation of training. However, due to the small number of earlier studies it is somewhat unclear whether the aquatic training-induced benefits can be maintained after cessation of training.

TABLE 3 Randomized controlled trials including aquatic training in persons with knee OA or knee replacement.

Reference	Participants, mean age	Study groups	Duration and frequency, follow-up	Progression, resistance	Changes in performance-based mobility and self-reports	Changes in muscle strength
Foley et al. 2003	Knee/hip OA 71 years	AT n=35 GYM n=35 C n=35	6 weeks 3 x week	Progr ADD	**Mobility** AT: +* L: +* C: 0 **Pain** AT: – L: 0 C: 0 **Stiffness** AT: 0 L: 0 C: 0 **Funct diff** AT: – L: – C: 0	**Isometric muscle strength** Knee extension AT: +* GYM: +* C: 0
Cochrane et al. 2005	Knee/hip OA 70 years	AT n=153 C n=159	1 year 2 x week 6 month FU	Progr ADD	**Mobility** AT: +* C: + **Pain** AT: -* C: + **Stiffness** AT: 0 C: 0 **Funct diff** AT: -* C: +	**Isometric muscle strength** Knee extension AT: + C: - Knee flexion AT: + C: +
Fransen et al. 2007	Knee/hip OA 70-71 years	AT n=55 TaiChi n=56 C n=41	12 weeks 2 x week 12 week FU	NoADD	**Mobility** AT: +* L: +* C: 0 **Pain** AT: -* L: - C: - **Funct diff** AT: -* L: -* C: -	
Hinman et al. 2007	Knee/hip OA 62-63 years	AT n=36 C n=35	6 weeks 2 x week 6 week FU	Progr NoADD	**Mobility** AT: +* C: 0 **Pain** AT: – * C: 0 **Stiffness** AT: –* C: – **Funct diff** AT: –* C: +	**Isometric muscle strength**[#] Hip abduction AT: +8-12%* C: – 3-6% Knee extension AT: +11-12% C: 1-2%
Wang et al. 2007	Knee or hip OA 66 years	AT n=20 C n=18	12 weeks 3 x week	Progr NoADD	**Mobility** AT: +* C: + **Pain** AT: – C: – **Funct diff** AT: 0 C: 0	**Isometric muscle strength** AT: Knee extension +19%*, flexion +12%* Hip extension +26%*, flexion +12%*, abduction +25%*, adduction +14%* C: 0

(Continues)

TABLE 3 Continues

Reference	Participants, mean age	Study groups	Duration and frequency, follow-up	Progression, resistance	Changes in performance-based mobility and self-reports	Changes in muscle strength
Lund et al. 2008	Knee OA 68 years	AT n=27 L n=25 C n=27	8 weeks 2 x week 12 week FU	Progr NoADD	**Pain** AT: 0 L: 0 C: 0	**Isokinetic muscle torque** Knee extension AT: –* L: +* C: 0 Knee flexion AT: –* L: +* C: 0
Silva et al. 2008	Knee OA 59 years	AT n=32 L n=32	18 weeks 3 x week	Progr ADD	**Mobility** AT: + L: + **Pain** AT: – L: – **WOMAC index** AT: – L: –	
Gill et al. 2009	Waiting for Knee/hip REPL 70 years	AT=42 L=40	6 weeks 2 x week FU 8 week PO	Progr No ADD	**Mobility** AT: + L: + FU AT: - L: - **Pain** AT: - L: - FU AT: 0 L: + **Funct diff** AT: - L: - FU AT: 0 L: +	
Lim et al. 2010	Obese with knee OA 66 years	AT n=26 L n=25 C n=24	8 weeks 3 x week	AT: NoADD L: ADD	**Pain** AT: -* L: - C: + **Funct diff** AT: -* L: -* C: -	**Isokinetic muscle torque** Knee extension AT: + L: + C: + Knee flexion AT: 0 L: + C: +
Wang et al. 2011	Knee OA 68 years	AT n=28 L n=28 C n=28	12 weeks 3 x week	Progr NoADD	**Mobility** AT: +* L: +* C: + **Pain** AT: -* L: -* C: 0	
Hale et al. 2012	Knee OA with fall risk 74 years	ATbal n=23 C n= 16	12 weeks 2 x week	Progr NoADD	**Mobility** AT: + C: + **Pain** AT: + C: - **Stiffness** AT: 0 C: - **Funct diff** AT: 0 C: -	
Harmer et al. 2009	Knee REPL 2 weeks PO 68 years	AT n=53 L n=49	6 weeks 2 x week 26 week FU	NoADD	**Mobility** AT: +* F-U L: + **Pain** AT: – L: – **Stiffness** AT: –* F-U L: – **Funct diff** AT: –* F-U L: –	

(Continues)

TABLE 3 Continues

Reference	Participants, mean age	Study groups	Duration and frequency, follow-up	Progression, resistance	Changes in performance-based mobility and self-reports	Changes in muscle strength
Rahmann et al. 2009	Knee/hip REPL 4 days PO 70 years	AT n=17 WE n=19 FS n=17	2 weeks 1 x day 12, 24 week FU	Progr NoADD	**Mobility** AT: – WE: – FS: – **WOMAC** AT: – WE: – FS: –	**Isometric muscle strength** Hip abduction AT: 0* WE: –17% L: –31%
Liebs et al. 2012	Knee/hip REPL 6/14 days PO 67-71 years	Day6=225 Day14=240	3-4 weeks 3 x week	NoADD	**Pain** AT6: – AT14: – **Stiffness** AT6: – AT14: – **Funct diff** AT6: – AT14: –	

OA= Diagnosed osteoarthritis, REPL= Replacement, PO= Postsurgery.

AT= Aquatic training, C= Non-training control group, L= Land-based training, GYM= Gym-based training, TaiChi= Tai Chi training, ATbal= Aquatic training targeted on improving balance, FS= Functional and strengthening exercises, WE= Nonspecific water exercise, FU= Follow-Up.

Progr= Progressive training program, ADD= Additional resistance in majority of the exercises, NoADD= Water as a resistance or small resistance (e.g. floaters) in some exercises only, Funct diff= Physical functional difficulty, WOMAC= Western Ontario and McMaster Universities Osteoarthritis Index.

+ Increased, - Decreased, 0 No change, (+, -, 0 estimated from the group mean values), * Significant difference between the groups, # Calculated from the group mean values.

2.4 Summary of the literature

Knee OA is a progressive, degenerative joint disease that causes severe pain and stiffness in the knee joint (Haq et al. 2003, Das & Farooqi 2008). These problems result in disuse of the painful limb and relate to mobility limitation (Liikavainio et al. 2008, Petterson et al. 2011). Knee replacement is a common surgical procedure that effectively relieves knee pain, and thus functional disability (NIH Consensus Panel 2004, Wylde et al. 2007, Nilsdotter et al. 2009b). After successful knee replacement surgery, mobility usually improves, but it rarely reaches the level of the age-matched control subjects (Walsh et al. 1998, Yoshida et al. 2008).

Mobility limitation can be explained by impairments in muscle torque and power (Yoshida et al. 2008, Petterson et al. 2009), which have been clearly shown to exist in knee OA and also after knee replacement on the affected side compared to the non-affected one (Lorentzen et al. 1999, Gapeyeva et al. 2007, Petterson et al. 2011, Barker et al. 2012). Additionally, it is noteworthy that the asymmetrical muscle deficit, that is muscle side-to-side difference between the legs, may as well explain mobility limitation. This was shown earlier in persons with unilateral muscle impairments due to hip fracture (Portegijs et al. 2008). However, it is not known whether the asymmetrical deficit in muscle power, torque and CSA in persons with knee OA and related knee replacement explains mobility limitation.

As the mobility limitation and muscle impairments related to knee OA and knee replacement are substantial, the need to develop efficacious rehabilitation methods exists. Water is an effective and pain-free training medium for persons with medical conditions that may restrict training on land. Previous RCTs have found positive effects on mobility and muscle strength after aquatic resistance training in healthy persons (Pöyhönen et al. 2002, Takeshima et al. 2002, Tsourlou et al. 2006) and in clinical populations (Foley et al. 2003, Cochrane et al. 2005, Wang et al. 2007). Also, aquatic training without additional resistance has somewhat been studied in the acute phase after knee replacement (Harmer et al. 2009, Rahmann et al. 2009). However, it is not known whether aquatic resistance training with additional resistance is effective in decreasing mobility limitation and muscle impairments after knee replacement. In addition, it is not clear whether the training-induced benefits can be maintained after cessation of training.

3 PURPOSE OF THE STUDY

The purpose of this study was to determine asymmetrical lower limb muscle deficits, and their associations with mobility limitation in persons with end-stage knee joint OA and in persons who have had knee replacement surgery. Thereafter, the effects of 3-month aquatic resistance training in persons with knee replacement were studied in a randomized controlled trial (RCT). The aquatic training program was specifically targeted at improving lower limb muscle power and torque of both lower legs, and reducing asymmetrical muscle deficit, and thus mobility limitation. The maintenance of training-induced benefits was studied 12 months after cessation of training.

We hypothesized that the asymmetrical deficit in lower limb muscles would exist, and it would be associated with mobility limitation (Studies I-II). Aquatic resistance training would reduce knee OA and knee replacement related mobility limitation by reducing muscle impairments and asymmetrical muscle deficit (Study III), and training-induced benefits would be maintained by regular physical activity after the exercise intervention (Study IV).

The specific research questions were:

1. Is there asymmetrical deficit in knee extensor and flexor muscle power, torque and CSA in persons with end-stage knee OA and in persons with knee replacement? (Studies I and II)
2. Is asymmetrical deficit in lower limb muscle power, torque or CSA associated with mobility limitation in persons with end-stage knee OA and in persons with knee replacement? (Studies I and II)
3. Does the aquatic resistance training have an effect on knee extensor and flexor muscle power, torque, CSA, asymmetrical muscle deficit, walking speed and stair ascension time in persons 4 to 18 months after knee replacement? (Study III)
4. Are the training-induced benefits in muscle power, torque, CSA, asymmetrical muscle deficit, walking speed and stair ascension time maintained in persons with knee replacement 12 months after cessation of training? (Study IV)

4 METHODS

4.1 Study design and participants

For this study, data from two research projects, knee osteoarthritis (KNEE-OA) and knee replacement (KNEE-REPLACEMENT), were used. KNEE-OA is a clinical experimental RCT of the rehabilitation of patients suffering from end-stage OA of the knee joint. The data was collected in Kymenlaakso Central Hospital between May 2008 and May 2012. KNEE-REPLACEMENT is a clinical experimental RCT on the effects of 3-month aquatic resistance training including patients recovering from unilateral knee replacement. The data was collected in Kymenlaakso Central Hospital between March 2005 and December 2006. The study design, participants and main outcome variables used in the original publications are summarized in Table 4.

TABLE 4 Description of the study designs, participants and main outcomes.

Study	Research project	Design	Participants	Age (Mean ± SD)	Main outcomes
I	KNEE-OA	**Observational** Cross-sectional	43 participants Women n= 23 Men n= 20	50-75 (65.4 ± 6.7)	KEP, KFP, KET, KFT, CSA Asymmetrical muscle deficit Maximal walking speed Stair ascension Physical functional difficulty, pain, stiffness
II	KNEE-REPLACEMENT	**Observational** Cross-sectional	48 participants Women n= 29 Men n= 19	55-75 (66.7 ± 5.9)	KEP, KFP, KET, KFT, CSA Asymmetrical muscle deficit Maximal walking speed Stair ascension
III	KNEE-REPLACEMENT	**Experimental** RCT 3-month intervention	50 participants Intervention group n= 26 Control group n= 24	55-75 (65.9 ± 6.1)	KEP, KFP, CSA Maximal and habitual walking speed Stair ascension Physical functional difficulty, pain, stiffness
IV	KNEE-REPLACEMENT	**Experimental** RCT 3-month intervention with 12-month post-intervention follow-up	42 participants Intervention group n= 25 Control group n= 17	55-75 (66.1 ± 5.9)	KEP, KFP, CSA Habitual walking speed Stair ascension Physical functional difficulty, pain, stiffness

KNEE-OA= Research project studying persons with knee osteoarthritis, KNEE-REPLACEMENT= Research project studying persons with knee replacement, RCT= Randomized controlled trial, SD= Standard deviation, KET= Knee extensor torque, KFT= Knee flexor torque, KEP= Knee extensor power, KFP= Knee flexor power, CSA= Muscle cross-sectional area.

4.1.1 KNEE-OA research project (Study I)

The KNEE-OA research project investigates mobility limitation, muscle function impairments, perceived functional difficulty and rehabilitation of persons with unilateral end-stage knee OA. Baseline cross-sectional data of participants was utilized in this study (Study I). The data were collected in two phases. Data collection was conducted with the same recruitment protocol, infrastructure and staff for all measurements.

The target population consisted of community-living 50-75-year-old women and men from the Kymenlaakso Central Hospital district, suffering with end-stage knee OA and awaiting knee replacement surgery. All eligible patients who were on the waiting list for a unilateral knee replacement in the local Central Hospital were informed of the study.

The flow chart of the research project is displayed in Figure 3. Physical examination, radiographs and pain history of the OA knee (the knee with end-stage knee OA with pending knee replacement) were evaluated from 123 patients by an orthopedic surgeon. Eighty-six women or men with medial knee OA according to a radiographic grading of Kellgren/Lawrence (K/L) K/L 3 or K/L 4 (Kellgren & Lawrence 1957) and continuous pain lasting at least six months were added to the waiting list for total knee replacement. Patients with posttraumatic OA, earlier osteotomy of the knee, rheumatoid arthritis, alcoholism, severe cardiovascular diseases, dementia or other diseases that decrease cooperation were excluded from the study. Fifty-two patients met the inclusion criteria and were informed about the present study. All eligible patients, who were willing to participate in this study were contacted by research personnel. Thus, 43 volunteers, 23 women and 20 men participated in the observational cross-sectional study (Study I).

4.1.2 KNEE-REPLACEMENT research project (Studies II-IV)

The KNEE-REPLACEMENT research project investigates mobility limitation, muscle function impairments, perceived functional difficulty and rehabilitation of persons with knee replacement. Cross-sectional data from participants at baseline were utilized (Study II), and the effects of aquatic resistance training aiming to improve lower extremity muscle strength and power, and thus mobility, were studied in a 3-month RCT (ISRCTN50731915) (Study III). The maintenance of training induced benefits was investigated after 12-months of follow-up (Study IV). The data were collected in two phases. Due the small number of eligible subjects in spring 2005, the data collection was repeated in autumn 2005 with the same recruitment protocol, infrastructure and staff for the measurements and training. The data were pooled for the analysis.

The target population consisted of community-living 55-75-year-old women and men from the Kymenlaakso Central Hospital district with unilateral knee replacement surgery due to medial tibiofemoral joint OA. To assure safety in the muscle power and torque measurements, the post-operative time for the participants was defined to be within 4 to 18 months prior to baseline. Patients living within a 30 km radius of the hospital with unilateral knee replacement were identified from the records of Kymenlaakso Central Hospital and invited to participate in the study. Persons with bilateral knee replacement, revision knee replacement, severe cardiovascular diseases, dementia, rheumatoid arthritis or any other major surgery in either of the knees were excluded from the study.

The flow chart of the research project is displayed in Figure 4. A total of 201 patients with unilateral knee replacements were informed about the research project. Eighty-six patients responded and were contacted by the research personnel and interviewed over the telephone. Fifty-two eligible persons were invited to the baseline measurements. Before the measurements, two participants were excluded from the intervention due to health problems to assure safe measurements and training. Fifty persons (30 women, 20 men) participated in the baseline measurements. The participants with partial knee replacement were excluded from the cross-sectional study (Study II) to confirm the homogeneity of the sample. Thus, 48 eligible volunteers with total knee replacement (age range 55-75 years), 29 women and 19 men, participated in the cross-sectional study (Study II).

Those with partial knee replacament did not differ from the participants with total knee replacement in any of the variables measured (power, torque, muscle CSA, maximal and habitual walking speed, stair ascension, and physical functional difficulty, pain and stiffness) at baseline, and were thus included in the RCT to increase the size of the sample (Study III). Thus, 50 eligible volunteers, 30 women and 20 men, were randomly assigned after the baseline measurements, into an aquatic training (16 women, 10 men) and a control group (14 women, 10 men). The random allocation was concealed in sealed envelopes, sorted into blocks by sex, age and type of knee replacement. Envelopes were allocated into the intervention and control groups by using randomization ratio of 1:1 by drawing lots. The randomization was performed by a person who was blinded to the details of the study participants.

The maintenance of the training induced benefits was studied after a 12-month follow-up period (Study IV).

4.2 Ethics

The KNEE-OA and KNEE-REPLACEMENT research projects were conducted according to guidelines for good scientific and clinical practice laid down by the Declaration of Helsinki. Both studies were approved by the Ethical Committee of Kymenlaakso Central Hospital. Before the laboratory examinations, the participants were informed about the study and written, signed, informed consent was obtained.

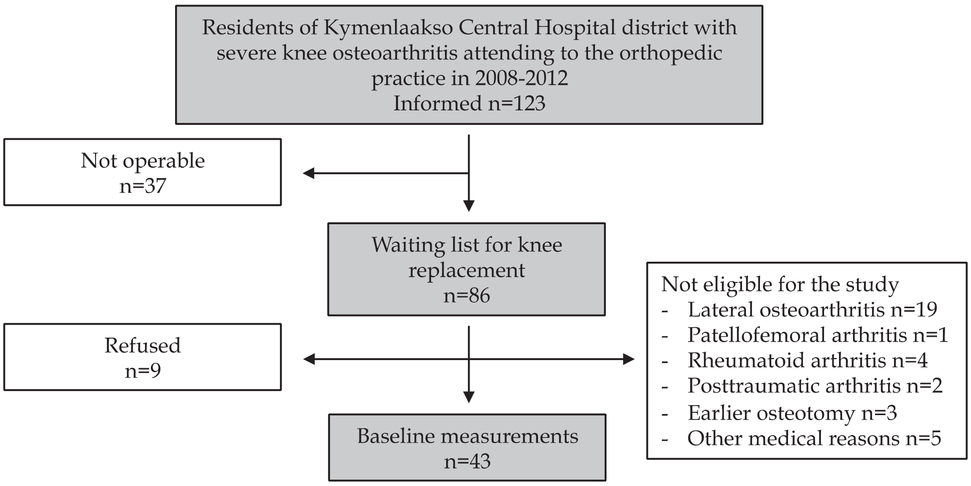

FIGURE 3 Flow chart of the KNEE-OA research project used in Study I.

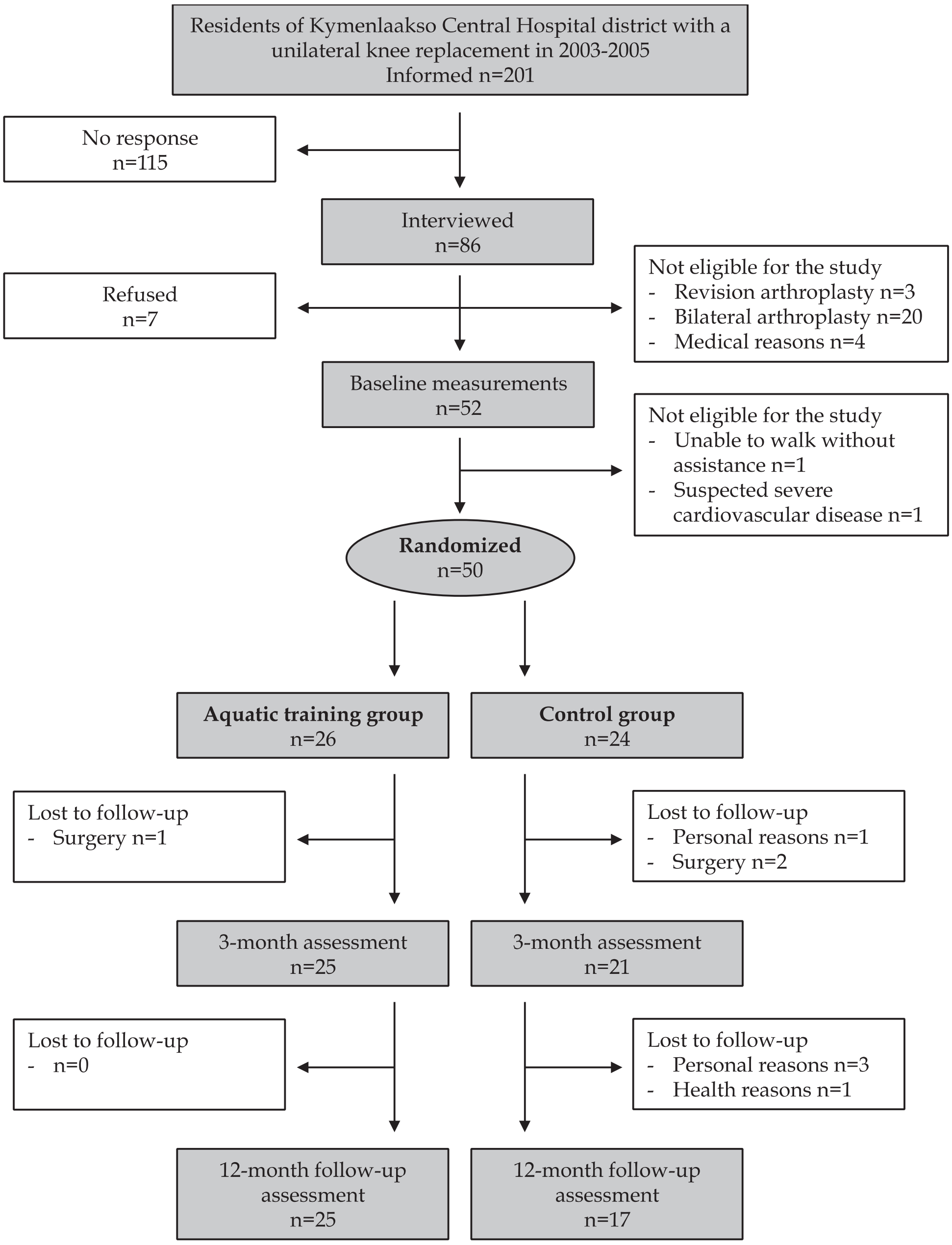

FIGURE 4 Flow chart of the KNEE-REPLACEMENT research project used in Studies II-IV.

4.3 Measurements

A summary of all the measurement methods used in Studies I-IV and their reliabilities are listed in Table 5. Computed tomography (CT) measurements and analyses were conducted blinded to the OA side (Study I) and operated side (Studies II-IV). Other measurements were conducted in a blinded manner in the KNEE-OA research project (Study I) and unblinded in the KNEE-REPLACEMENT research project (Studies II-IV).

4.3.1 Muscle function impairments

Muscle power and torque
Maximal voluntary power (the rate at which muscles can produce work; Studies I-IV) and torque (capability of force to produce rotation; Studies I-II) of the knee extensors and flexors were assessed for both lower limbs separately using an isokinetic dynamometer (Humac/Norm, Computer Sports Medicine, Inc., Stoughton, MA; Study I or Biodex Medical Systems, Inc., Shirley, NY; Studies II-IV) with a sampling frequency of 100 Hz and a 1% measurement error through the entire range of motion (Pöyhönen et al. 2002). The dynamometer was calibrated before each measurement session according to the standard procedure recommended by the manufacturer. Before the measurement session, the participants were carefully familiarized with the testing procedure. For each leg, the axis of rotation of the dynamometer was 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 the lateral malleolus. The hip and thigh were stabilized with straps. The measurement was performed on the full knee range of motion of the participant. After few submaximal flexion-extension movements, three maximal continuous flexion-extension trials were performed at an angular velocity of 60 degrees per second ($deg{\cdot}s^{-1}$) and 5 to 10 trials at a velocity of 180 $deg{\cdot}s^{-1}$. The inter-trial rest period was two to three minutes. The participants were verbally encouraged to make maximal effort throughout the whole range of motion. The performance of highest extensor and flexor torque (Nm) values at angular velocities of 60 $deg{\cdot}s^{-1}$ and 180 $deg{\cdot}s^{-1}$ were used for the analyses. Peak extensor and flexor power (W) were analyzed from the efforts with the angular velocity of 180 $deg{\cdot}s^{-1}$.

TABLE 5 Measurement methods and variables used in this study including reliability.

Variable	Study	Method	Reliability	Specifics
Outcome and explanatory variables				
Muscle power and torque				
Maximal isokinetic KEP and KFP (W)	I-IV	Isokinetic dynamometer, angular velocity 180 $deg{\cdot}s^{-1}$	ICC .90-.96 Our laboratory	Both sides
Maximal isokinetic KET and KFT (Nm)	I	Isokinetic dynamometer, angular velocity 180 $deg{\cdot}s^{-1}$	ICC .90-.96 Our laboratory	Both sides
Maximal isokinetic KET and KFT (Nm)	I-II	Isokinetic dynamometer, angular velocity 60 $deg{\cdot}s^{-1}$	ICC .91-.97 Our laboratory	Both sides
Muscle CSA and attenuation				
Muscle CSA (cm^2)	I-IV	Computed tomography	CV 1-2% Sipilä et al. 1995	Both sides
Attenuation (HU)	I	Computed tomography	CV 1% Sipilä et al. 1995	Both sides
Mobility limitation				
10 meter maximal walking speed ($m{\cdot}s^{-1}$)	I-III	Stopwatch (I)/Photocells (II-III)	ICC .86 Our laboratory	
10 meter habitual walking speed ($m{\cdot}s^{-1}$)	I-IV	Stopwatch (I)/Photocells (II-IV)	ICC .44 Our laboratory	
Stair ascension time (s)	I-IV	Stopwatch (I)/Photocells (II-IV)	ICC .73 Our laboratory	
Self-reports				
WOMAC pain (mm)	I-IV	WOMAC pain index		Affected side
WOMAC stiffness (mm)	I,III-IV	WOMAC stiffness index		Affected side
WOMAC physical functional difficulty (mm)	I,III-IV	WOMAC physical functional difficulty index		
Descriptive variables				
Anthropometry				
Body weight (kg)	I-IV	Beam scale		
Body height (cm)	I-IV	Scale stadiometer		
Comorbidities (n)	I-IV	Self-report, confirmed by study personnel		
Knee OA burden (n)	I	Self-report, confirmed by study personnel		
Physical activity	III-IV	Self-report, confirmed by study personnel		

KEP= Knee extensor power, KET= Knee extensor torque, KFT= Knee flexor torque, KFP= Knee flexor power, CSA= Cross-sectional area, HU= Hounsfield unit, WOMAC= Western Ontario and McMaster University Osteoarthritis Index, Knee OA burden= Number of knees affected by knee osteoarthritis, CV= Coefficient of variation, ICC=Intraclass correlation coefficient.

Muscle cross-sectional area and attenuation
Muscle cross-sectional area (CSA; cm^2; Studies I-IV) and attenuation (HU; Studies I-II) were assessed with computed tomography (CT). CT scans were obtained from both mid-thighs using a Siemens Somatom Definition AS scanner (Siemens Ag, Erlangen, Germany; Study I) and a Siemens Somatom DR Scanner (Siemens Ag, Erlangen, Germany; Studies II-IV) with the patient in the supine position (Sipilä & Suominen 1995). The mid-thigh was defined as the midpoint between the level of the greatest lateral protuberance of the greater trochanter and lower edge of the patella. In the baseline measurements, the mid-thigh was marked out with a tattoo. The scans were analyzed using an Agfa Impax ES DS3000 Radiology Diagnostic Station (Agfa HealthCare NV, Mortsel, Belgium; Study I) and software developed for cross-sectional CT image analysis (Geanie 2.1, Commit Ltd, Espoo, Finland; Studies II-IV), which separate fat and lean tissue based on the radiological density limits (measured as attenuation in Hounsfield units). A lower mean attenuation value reflects greater fat infiltration within the muscle.

Asymmetrical muscle deficit
In cross-sectional analyses (Studies I-II) the relative difference in muscle power and torque, and muscle CSA between the OA side and contralateral side (Study I) and the operated and non-operated side (Study II) were calculated according to Formula 1 and Formula 2 and used as a measure for asymmetrical muscle deficit. The value 0% represents equal values in both lower legs, indicating no asymmetrical muscle deficit. Positive values indicate lower value on the OA side (I) or on the operated side (II) (Portegijs et al. 2005).

FORMULA 1: $\frac{(Contralateral - OA)}{Contralateral} \times 100$ [%]

FORMULA 2: $\frac{(Nonoperated - Operated)}{Nonoperated} \times 100$ [%]

In additional analyses published in this thesis to show the training effect on asymmetrical muscle deficit, the relative difference in knee extensor and flexor power between the operated and non-operated side was calculated according to Formula 3 and used as a measure of asymmetrical muscle deficit. The value of 50% represents equal values in both legs, indicating no asymmetrical muscle deficit. Values below 50% indicate lower value on the operated side (Portegijs et al. 2008).

FORMULA 3: $\frac{Operated}{(Operated + Nonoperated)} \times 100$ [%]

4.3.2 Mobility limitation

Maximal walking speed ($m \cdot s^{-1}$; Studies I-III) (Rantanen & Avela 1997) and habitual walking speed ($m \cdot s^{-1}$; Studies III-IV) (Portegijs et al. 2008) over 10 meters were assessed in the hospital corridor and the time taken for walking was recorded using a stopwatch (Study I) or photocells (Newtest Oy, Oulu, Finland; Studies II-IV). All the participants wore thin aquatic shoes and were allowed three meters for acceleration. They were instructed to walk as fast as possible without compromising their safety. Each participant made two efforts for both speeds separated by a 1-minute rests and the faster performances were accepted for statistical analysis.

Maximal stair ascension time (s; Studies I-IV) over 10 stairs was measured in the hospital corridor (Gur & Cakin 2003). The time taken for ascension was recorded using a stopwatch (Study I) or photocells (Newtest Oy, Oulu, Finland; Studies II-IV). The stair height was 17 cm and depth 29.5 cm. The participants were instructed to step alternately on each stair and ascend as fast as possible without compromising their safety. A handrail or taking a step with both feet on the same step (bipedal ascent) was allowed only if necessary. Each participant performed two trials of stair ascension separated by a 1-minute rest. The time of the faster performance was accepted for statistical analysis.

4.3.3 Pain, stiffness and physical functional difficulty

The WOMAC questionnaire (Western Ontario and McMaster University Osteoarthritis Index) (Bellamy et al. 1988) was used to assess the level of pain (5 subscales) and stiffness (2 subscales) in the OA knee or operated knee and the physical functional difficulty (17 subscales) of the participants (Studies I, III-IV). The subscales were based on the visual analogue scale (VAS, range 0-100mm, with 100 indicating the worst possible situation). The WOMAC indexes are the sum of the related subscales divided by the number of subscales used. In the physical functional difficulty score, 65% of the participants study did not answer the subscale 'getting in and out of the bath' because they did not have a bath. Therefore, this subscale was not included in the analysis.

4.3.4 Health status and background characteristics

Contraindications for safe participation
The general health, clinical history, medication, and diseases of the participants were assessed by a physician before the laboratory examinations to evaluate potential contraindications for safe participation in the measurements and training.

Anthropometry
Body height and body weight (Studies I-IV) were measured in the hospital laboratory using standard procedures.

General health
Diseases and regular medication were assessed by self-reports and confirmed by research personnel (Studies I-IV).

Physical activity
The level of general physical activity was assessed by a questionnaire (Studies III-IV). Participants were asked about their type of physical exercises and general physical activity that they perform, as well as the frequency (times per week) and duration (minutes per session) of the physical activity. Additionally, participants were asked to estimate the loading of the physical activities they perform on scale 1 to 3 where '1' represents light, '2' moderate, and '3' heavy.

Knee status
In persons with knee OA, the radiographs (K/L grading, See Table 1 in chapter 2.1) and the pain history of the OA knee were evaluated by an orthopedic surgeon. The OA burden of the contralateral knee was collected by self-report. Both knees were assessed for OA and a sum (one or two) was used to describe the burden of knee OA. If the contralateral knee was replaced, it was considered to have OA burden.

In persons with knee replacement the characteristics of the knee replacement surgery were collected from the hospital medical records. Forty-eight participants (96%) had undergone tri-compartmental total knee replacement and two participants (4%) had unicompartmental partial knee replacement. All knee replacements were fixed with cement. The OA burden of the non-operated knee was collected by self-report and a sum (one or two) was used to describe the burden of knee OA.

4.4 Aquatic training intervention

In the KNEE-REPLACEMENT research project, participants without contraindications for the aquatic training participated in the RCT. The aim of the training was to improve muscle power, torque and muscle mass in the lower legs, and thus mobility. A 3-month aquatic training for the participants of the training group was conducted in the hospital therapy pool twice a week in small classes including 4-5 participants. The classes were supervised by an experienced physiotherapist. The training compliance was calculated according to Formula 4.

FORMULA 4: $\frac{Attended}{Offered} \times 100$ [%]

4.4.1 Aquatic training exercises

Each session started with an 8 min warm-up including walking (forward, backward, sideways), aqua jogging and lower leg muscle stretching. Warm-up was followed by 30-40 min of resistance training and a 5 min cooling down period. Each training session consisted of five exercises for both legs, which were selected on the basis our previous study (Pöyhönen et al. 2002): 1) 1-leg knee extension-flexion movement in a sitting position, 2) hip abduction-adduction with extended knee in a standing position, 3) hip extension-flexion with extended knee in a standing position, 4) 1-leg knee extension-flexion in a standing position and 5) step-squat backwards from the aqua aerobic step board.

In each exercise, the operated side was trained first. The operated side was trained to 30% more sets compared to the non-operated one. Table 6 summarizes the training program including the weekly sets, duration of work and rest and resistance produced by the resistance-boots.

The subjects were instructed to perform each repetition with maximal effort in order to achieve the highest possible movement velocity and resistance. Verbal encouragement was provided by the instructor and the participants were asked to describe their perceived exertion after each exercise with the RPE scale (6-20) (Borg 1998). Training was conducted by heart rate response monitoring to control the level of work and recovery. A physician was consulted for all medical symptoms and any pain that emerged during the training.

TABLE 6 Summary of the aquatic training protocol.

Week	Sets		Reps	Work/set	Rest/set	Resistance	Mean RPE
	Operated	Non-operated		(s)	(s)		
1	2	2	25-30	45	30	No boots	14
2	2	2	25-30	45	30	No boots	15
3	2	2	20-25	35	30	Small	16
4	3	2	20-25	35	30	Small	16
5	2	2	14-20	30	30	Medium	16
6	2	2	14-20	30	30	Medium	17
7	3	2	25-30	40	30	No boots	16
7	3	2	14-20	30	30	Medium	16
8	3	2	14-20	30	30	Medium	17
9	2	2	12-15	30	30	Large	17
10	3	2	12-15	30	40	Large	16
11	4	2	12-15	30	40	Large	17
12	3	2	12-15	30	40	Large	17
12	3	2	25-30	30	40	No boots	16

Operated= Side with knee replacement, Non-operated= Side without knee replacement, Reps= Repetitions, RPE= Rating of Perceived Exertion.

4.4.2 Progressive resistance

The progression of the exercise program was ensured by using four different resistances: 1) without resistance boots, 2) with small, 3) medium or 4) large resistance boots and by varying the amount and duration of sets. The first two weeks of training were conducted without resistance boots in order to ensure adaptation to the exercises. The actual training was conducted using small size Aqua Runner Zero Impact Footwear (AquaJogger, Springfield, OR, USA) and with medium and large size resistance boots (Hydro-Tone Fitness Systems, Inc., Orange, CA, USA) with frontal areas of 0.045 and 0.075 m^2, respectively.

The small footwear were attached around the foot, and the medium and large size boots around the lower leg and foot during the exercises. In weeks 7 and 12, one training session was conducted without resistance boots in order to avoid overtraining. The drag during the exercises has been estimated to be double with the medium size boots and triple with the large boots compared to the barefoot condition (Pöyhönen et al. 2002).

4.4.3 Intensity of training

The intensity of training was defined during the exercises by the RPE (Borg 1998). In addition, the training intensity was estimated for six persons (3 women, 3 men) from the training group (mean age 62.2±4.3 years, body height 169.8±8.2 cm, body weight 86.3±9.2 kg) with heart rate monitoring (Polar RS400, Polar Electro Oy, Kempele, Finland).

The average heart rates were recorded during the five exercises excluding the warm-up and cool-down. Age-related maximal heart rates were calculated according to Formula 5.

FORMULA 5: $220\ (beats/min) - age\ (years)$ [beats/min]

The mean average heart rate was 116±18 beats/min (range 93-148), which was 73% of age-related maximal heart rate. In the hydro-boot conditions the movement velocities were slower and the number of repetitions per set were lower but the resistance was higher compared to the barefoot condition (Pöyhönen et al. 2001a, Pöyhönen et al. 2002).

4.4.4 Control group

The control group did not receive any intervention. The participants were encouraged to continue their lives as usual during the 3-month trial.

4.5 Statistical analyses

Means and standard deviations (SD) were used as descriptive statistics. The normality distributions were tested using Kolmogorov-Smirnov tests. In the baseline comparisons the absolute differences in muscle variables (power, torque, CSA, and attenuation) between the OA and contralateral side (Study I), and between the operated and the non-operated side (Study II) were analyzed with a paired 2-tailed Student's *t* test.

In participants with knee OA (Study I) and with knee replacement (II-IV), statistical tests were first performed separately for women and men. Since there were no differences between the sexes in age or in any of the asymmetrical muscle deficit variables the results obtained for men and women were pooled to obtain a larger sample size.

Linear regression models

Stepwise multiple linear regression models were used to examine the determinants associated with mobility limitation. Variables with non-significant independent associations with mobility were removed from the final model. Thus, the final models contained only the explanatory variables that had significant independent associations with mobility limitations and that had the highest possible proportion of the variance explained by coefficients of determination (adjusted r^2). The models were further adjusted for age and sex (Studies I-II) and time after surgery (Study II).

Analysis of covariance

Analysis of covariance (ANCOVA) was used to assess the post-trial (Study III) and follow-up (Study IV) training effects between the training and control groups. Age, sex and postoperative time were tested separately and they were added into the model as covariates. Since they did not have an effect on the results, only the baseline measurement was used as a covariate.

Training effect

For each participant, the relative changes in knee extensor and flexor power and torque, thigh CSA and mobility measures between the pre- and post-trial measurements (Study III) were calculated according to Formula 6, and between pre-trial and follow-up measurements (Study IV) according to Formula 7. For asymmetrical muscle deficits, the change in time was calculated according to Formulas 8 and 9.

FORMULA 6: $\frac{(Post-Pre)}{Pre} \times 100$ [%]

FORMULA 7: $\frac{(Follow\ up-Pre)}{Pre} \times 100$ [%]

FORMULA 8: $Post - Pre$ [%]

FORMULA 9: $Follow\ up - Pre$ [%]

The training effect (the mean difference) between the mean relative changes and 95% confidence intervals (CI) of the aquatic training and control groups between the pre- and post-trial measurements (Study III), and pre-trial and follow-up measurements (Study IV) were calculated according to Formula 10.

FORMULA 10: $Aquatic\ training - Control$ [%]

Statistical power
For the RCT (Study III), all results were based on an Intention-to-treat analysis. All the eligible patients with knee replacement were included in the study and thus, with the present dropout rate, the sample size of the study provided 80% statistical power to detect a difference of about 10% between the groups in habitual walking speed at a significance level of $p<0.05$.

In all studies, SPSS software (SPSS Inc., Chicago, IL, versions 13.0, 17.0 or 19.0) was used for analysis and statistical significance was set at $p<0.05$.

5 RESULTS

5.1 Participant characteristics

The study population consisted of community-dwelling people aged between 50 and 75 years. Table 7 displays the characteristics of persons with knee OA and knee replacement. Persons with knee OA were on average 65 years old. The WOMAC pain index of the OA knee was on average 44/100 and the contralateral knee had an OA burden in 26% of the participants. Persons with knee replacement were on average 66 years old and their mean post-operative time was 10 months. The WOMAC pain index of the operated knee was 17/100 and the non-operated knee had an OA burden in 16% of the participants. Additionally, Table 7 shows the baseline physical characteristics of the training and control groups used in the RCT (Study III).

5.2 Muscle function impairments and asymmetrical muscle deficit

Muscle power and torque
In persons with knee OA (Study I) the knee extensors and flexors on the OA side were significantly weaker compared to the contralateral side ($p<0.001$; Table 8; Figure 5). Mean±SD asymmetrical deficit in knee extensor power was 24±21%, in torque at 180 $deg{\cdot}s^{-1}$ 22±20% and in 60 $deg{\cdot}s^{-1}$ 30±19%. In knee flexors the corresponding asymmetrical muscle deficits were 21±31%, 23±30% and 21±31%, respectively.

In persons with knee replacement (Study II) the knee extensors and flexors on the operated side were significantly weaker compared to the non-operated side ($p<0.001$; Table 8; Figure 5). Mean±SD asymmetrical deficit in knee extensor power was 23±20%, torque at 180 $deg{\cdot}s^{-1}$ 23±18% and at 60 $deg{\cdot}s^{-1}$ 27±17%. In knee flexors the corresponding asymmetrical muscle deficits were 19±27%, 13±23% and 13±19%, respectively.

TABLE 7 Participant characteristics in participants with end-stage osteoarthritis of the knee joint (Study I), and participants 4-18 months after knee replacement surgery (Studies II-IV).

	Knee OA	Knee replacement		
	I	II	III-IV#	
	All n=43	Total knee replacement n=48	Training group n=26	Control group n=24
Variables	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Age, years	65.4 ± 6.7	66.3 ± 6.0	66.2 ± 6.3	65.7 ± 6.0
Body mass, kg	83.4 ± 14.4	83.2 ± 15.1	83.2 ± 15.2	83.9 ± 15.0
Body height, cm	168.2 ± 9.2	168.0 ± 8.6	167.3 ± 9.3	169.7 ± 8.2
Comorbidities, n	1.8 ± 1.4	1.4 ± 1.2	1.7 ± 1.2	1.2 ± 1.1
Time after surgery, months	-	9.6 ± 4.5	9.9 ± 4.7	9.2 ± 4.2
Pain of the OA knee, 0-100	44.3 ± 19.7	-	-	-
Pain of the operated knee, 0-100	-	16.9 ± 12.9	16.3 ± 10.6	16.9 ± 14.9
	n (%)	n (%)	n (%)	n (%)
Women, n (%)	23 (53.5)	29 (60.4)	16 (61.5)	14 (58.3)

A total of eight participants were lost to follow-up (Study IV). For baseline characteristics of those who participated see Original paper IV.
Knee OA= Persons with knee osteoarthritis, Knee replacement= Persons with unilateral knee replacement.

TABLE 8 Isokinetic knee extensor and flexor muscle power, torque, thigh muscle CSA and attenuation in participants with end-stage osteoarthritis of the knee joint (Study I; n=43), and participants 4-18 months after knee replacement surgery (Study II; n=48). Differences between the OA side and the contralateral side, and between the operated side and the non-operated side were tested with paired samples t-test.

	Knee OA (Study I)			Knee Replacement (Study II)		
	OA side	Contralateral side		Operated side	Non-operated side	
Variable	Mean ± SD	Mean ± SD	*p*	Mean ± SD	Mean ± SD	*p*
Knee extensors						
Power 180 deg·s^{-1}, W	139.8 ± 62.6	190.0 ± 83.0	<0.001	117.3 ± 47.1	153.6 ± 55.0	<0.001
Torque 180 deg·s^{-1}, Nm	51.4 ± 19.7	67.5 ± 24.8	<0.001	56.7 ± 21.0	74.8 ± 24.2	<0.001
Torque 60 deg·s^{-1}, Nm	74.6 ± 28.9	107.5 ± 35.6	<0.001	79.6 ± 27.9	111.7 ± 37.7	<0.001
Knee flexors						
Power 180 deg·s^{-1}, W	98.1 ± 47.0	126.7 ± 52.0	<0.001	105.0 ± 44.1	133.9 ± 50.9	<0.001
Torque 180 deg·s^{-1}, Nm	31.5 ± 16.1	41.0 ± 17.4	<0.001	39.2 ± 15.8	45.6 ± 16.3	<0.001
Torque 60 deg·s^{-1}, Nm	44.3 ± 22.0	56.6 ± 25.3	<0.001	53.8 ± 21.2	62.2 ± 22.4	<0.001
Thigh muscle						
CSA, cm^2	133.2 ± 26.3	139.9 ± 29.2	<0.001	101.4 ± 25.9	111.5 ± 27.3	<0.001
Attenuation, HU	37.7 ± 9.7	39.7 ± 9.4	<0.001	35.6 ± 5.1	37.8 ± 4.3	<0.001

Knee OA= Persons with knee osteoarthritis, Knee replacement= Persons with unilateral knee replacement, OA side= Side with knee with end-stage osteoarthritis awaiting knee replacement, Contralateral side= Side with 'better knee', which is not awaiting knee replacement, Operated side= Side with knee replacement, Non-operated side= Side without knee replacement, CSA= Cross-sectional area.

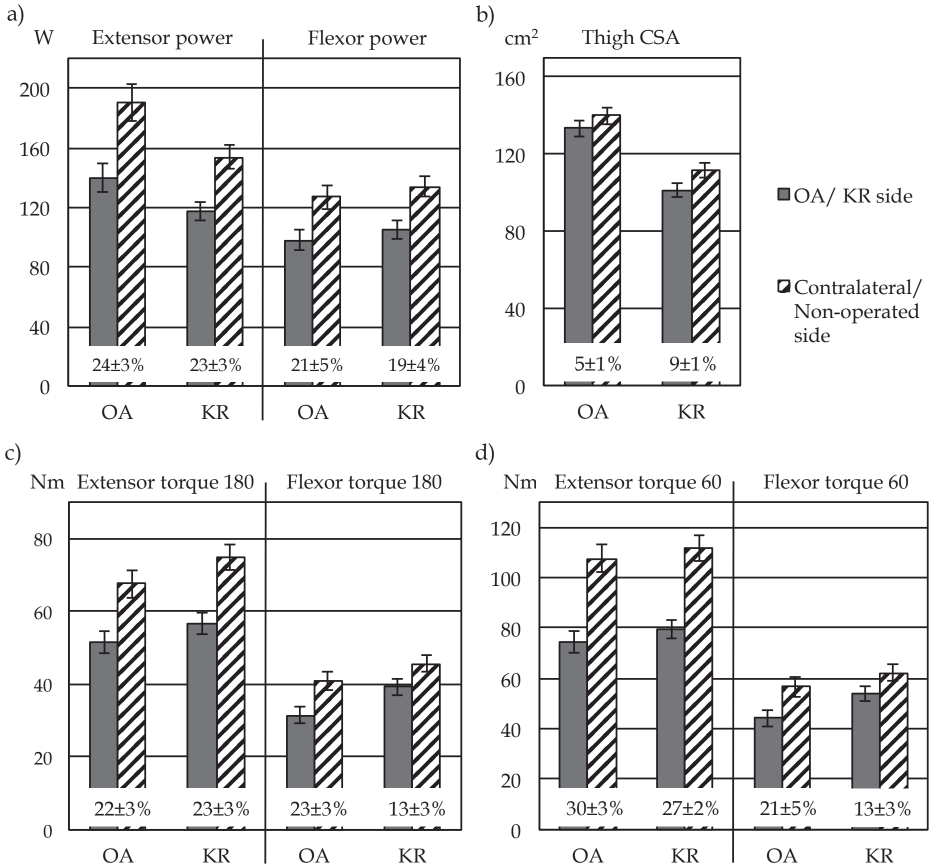

FIGURE 5 Means and standard error means of isokinetic muscle power at 180 deg·s^{-1} (a), thigh cross-sectional area (CSA) (b), isokinetic muscle torque at 180 deg·s^{-1} (c), and isokinetic muscle torque at 60 deg·s^{-1} (d) in knee extensors and flexors of the OA side/operated side and contralateral side/non-operated side in persons with knee osteoarthritis (OA) and in persons with knee replacement (KR). The mean asymmetrical muscle deficits and standard error means are noted at the base of the bars.

Muscle CSA and attenuation

In persons with knee OA (Study I) the thigh muscle CSA was significantly smaller and the attenuation coefficient was lower on the OA side compared to the contralateral side ($p<0.001$; Table 8; Figure 5). Lower attenuation coefficient in skeletal muscle describes higher fat infiltration with in the muscle compartment. Mean±SD asymmetrical deficit in thigh CSA was 5±5% and in the attenuation coefficient 5±9%.

In persons with knee replacement (Study II), the thigh muscle CSA was significantly smaller on the operated side compared to the non-operated side ($p<0.001$; Table 8; Figure 5). Mean±SD asymmetrical muscle deficit was 9±8% for thigh CSA and 6±6% for the attenuation coefficient.

5.3 Mobility limitation

In persons with knee OA (Study I) the mean maximal walking speed was 1.5±0.4 $m \cdot s^{-1}$ and the mean habitual walking speed 1.1±0.2 $m \cdot s^{-1}$ In persons with knee replacement (Study II) the mean maximal walking speed was 1.9±0.5 $m \cdot s^{-1}$ and the mean habitual walking speed was 1.3±0.2 $m \cdot s^{-1}$.

In persons with knee OA (Study I) the mean stair ascension time was 6.8±3.3 s. Eight participants (19%) were not able to perform alternate stepping and thus used bipedal ascent. In persons with knee replacement (Study II) the mean stair ascension time was 4.9±2.0 s. Four participants (8%) were not able to perform alternate stepping and used bipedal ascent.

5.4 Factors explaining mobility limitation

Regression analyses revealed that asymmetrical extensor power deficit was the most relevant asymmetrical muscle deficit variable associated with mobility limitation (Studies I-II). The final multivariate models (Table 9) show only the explanatory variables that had significant independent associations with mobility limitations.

Maximal walking speed was not associated with asymmetrical muscle deficit. However, in persons with knee OA, knee flexor power of the contralateral side together with WOMAC knee pain explained 44% of the variation observed in the walking speed. Also, in persons with knee replacement, knee flexor power of the non-operated side explained 30% of the variability in their walking speed. Adjustment for potential confounding factors did not materially change the associations.

In persons with knee OA, asymmetrical knee extensor power deficit, together with knee flexor power of the contralateral side, knee OA burden and WOMAC knee pain predicted 65% of the variation observed in stair ascension time. Additionally, in persons with knee replacement, asymmetrical knee extensor power deficit, together with knee flexor power of the non-operated side explained 37% of the variability in stair ascension time. Adjustment for potential confounding factors did not materially change the associations.

TABLE 9 Multivariate linear regression models explaining variability in maximal walking speed and in stair ascension time in persons with knee OA (Study I; n=43) and in persons with knee replacement (Study II; n=48). The crude models include only the significant determinants; asymmetrical knee extensor power deficit, knee flexor power of the contralateral/non-operated side, knee OA burden and WOMAC knee pain. The adjusted models are adjusted with age and sex in persons with knee OA and with age, sex and postoperative time in persons with knee replacement.

	Knee OA						Knee replacement					
	Crude			Adjusted			Crude			Adjusted		
	R^2	β	*p*	R^2	β	*p*	R^2	β	*p*	R^2	β	*p*
a) Maximal walking speed	0.437		<0.001	0.445		<0.001	0.299		<0.001	0.325		0.001
Flexor power of the contralateral/non-operated side, W		0.504	<0.001		0.488	0.003		0.547	<0.001		0.495	0.007
WOMAC pain of the OA/operated knee, 0-100		-0.366	0.006		-0.355	0.010		-	-		-	-
b) Stair ascension time	0.645		<0.001	0.670			0.372		<0.001	0.378		<0.001
Asymmetrical knee extensor power deficit %		0.319	0.003		0.313	0.004		0.404	0.002		0.379	0.006
Flexor power of the contralateral/ non-operated side, W		-0.548	<0.001		-0.577	<0.001		-0.481	<0.001		-0.423	0.021
Knee OA burden*, n		0.287	0.008		0.254	0.020		-	-		-	-
WOMAC pain of the OA/operated knee, 0-100		0.275	0.011		0.276	0.012		-	-		-	-

Knee OA= Persons with knee osteoarthritis, Knee replacement= Persons with unilateral knee replacement, Contralateral side= In persons with knee osteoarthritis the side with 'better knee', which was not awaiting knee replacement, Non-operated side= In persons with knee replacement the side without knee replacement, * Number of knees affected by knee OA.

5.5 Effects of aquatic resistance training and maintenance of training-induced benefits

Fifty participants with knee replacement participated in the RCT (Study III). In the training group the participants did not report any pain during the training program. However, one participant visited the study physician due to elevated blood pressure without taking further actions or a pause in the training regimen. Training compliance in the aquatic training sessions for those who completed the training was excellent, averaging 98% (590 sessions attended/ 600 offered). The mean RPE value for training was 16 (range 14-17). The drop-out rates were 4% and 13% in the training and control groups, respectively. In the training group one participant (due to knee replacement surgery of the contralateral knee) and in the control group three participants (one for personal reasons and two for a knee replacement surgery of the contralateral knee) were lost to 3-month assessment (See Figure 4).

Forty-two participants (84%) were measured in the follow-up assessment 12 months after cessation of training. All the participants from the training group participated in follow-up assessments, whereas four subjects in the control group withdrew from the study during the follow-up (See Figure 4). During the 12-month follow-up, two participants in the training group and one in the control group had their non-operated knee replaced. In addition, one participant in each group had revision knee replacement during the follow-up. At the follow-up measurements, two participants in the training group (asthma, sprain in the ankle) and one in the control group (sprain in the knee) had acute health problems, and consequently they attended only to the CT measurements and completed the questionnaires. During the 12-month follow-up, the habitual physical activity of the participants was at the same level in both groups. Three participants in the training and one in the control group had increased their habitual physical activity, and two participants in the training and three in the control group had decreased their habitual physical activity. None of the participants continued aquatic resistance training after the intervention.

5.5.1 Muscle function impairments and asymmetrical muscle deficit

At baseline, there were no differences between the aquatic training group and the control group in knee extensor and flexor power, torque, asymmetrical muscle deficit or thigh CSA (Table 10).

Training effects

Figure 6 shows a forest plot of the training effects (Study III). For absolute values see original paper III. The training group improved knee extensor power on the operated side by 32% and on the non-operated side by 10% compared with controls (ANCOVA $p<0.001$ and $p=0.008$, respectively). Training decreased asymmetrical knee extensor power deficit by 4% compared with the control group (p=0.015). Training increased knee flexor power on the operated and non-operated side by 48% and 8% compared with controls (p=0.003 and p=0.002, respectively). Training also decreased asymmetrical knee flexor power deficit by 5% compared with the control group (p=0.011).

The training group improved knee extensor torque on the operated side by 10% and on the non-operated side by 7% compared with controls (p=0.015 and p=0.019, respectively). Training had no effect on asymmetrical knee extensor torque deficit (p=0.318). Training increased knee flexor torque on the operated side by 21% compared with controls (p=0.013), but had no effect on the non-operated side (p=0.517). Training decreased asymmetrical knee flexor torque deficit by 3% compared with the control group (p=0.017).

Additionally, training increased thigh muscle CSA on the operated and non-operated side by 3% and 2% compared with controls (p=0.018 and p=0.019, respectively).

TABLE 10 Baseline values of main outcomes in the training and control groups (Study III).

	Intervention			Control			
Variable	n	Mean	95% CI	n	Mean	95% CI	p
KEP operated, W	25	114.9	(93.1 to 136.6)	24	125.1	(106.0 to 144.2)	0.440
KEP non-operated, W	26	154.8	(132.2 to 177.4)	24	157.6	(132.7 to 182.5)	0.974
KEP asymmetrical deficit, %	25	41.4	(38.0 to 44.9)	24	44.5	(42.7 to 46.4)	0.112
KFP operated, W	25	102.6	(81.8 to 123.3)	24	110.8	(93.6 to 128.1)	0.430
KFP non-operated, W	26	132.1	(112.9 to 151.4)	24	139.3	(115.7 to 162.9)	0.734
KFP asymmetrical deficit, %	25	42.4	(38.2 to 46.6)	24	45.0	(42.1 to 47.9)	0.297
KET operated, Nm	26	78.6	(65.2 to 92.1)	23	82.3	(72.3 to 92.3)	0.659
KET non-operated, Nm	25	110.2	(93.2 to 127.2)	23	115.1	(99.7 to 130.5)	0.662
KET asymmetrical deficit, %	25	41.5	(38.8 to 44.2)	23	42.0	(39.7 to 44.2)	0.794
KFT operated, Nm	26	54.6	(44.4 to 64.8)	23	52.7	(46.0 to 59.4)	0.764
KFT non-operated, Nm	25	63.6	(53.0 to 74.3)	23	61.8	(53.6 to 70.0)	0.779
KFT asymmetrical deficit, %	25	45.2	(42.4 to 48.0)	23	46.1	(44.1 to 48.2)	0.600
Thigh CSA operated, cm^2	24	105.2	(92.5 to 117.8)	19	101.5	(91.4 to 111.7)	0.657
Thigh CSA non-operated, cm^2	24	114.5	(102.2 to 126.8)	19	111.1	(98.9 to 123.4)	0.693
Habitual walking speed, $m{\cdot}s^{-1}$	26	1.3	(1.2 to 1.4)	24	1.3	(1.2 to 1.4)	0.684
Maximal walking speed, $m{\cdot}s^{-1}$	26	2.0	(1.8 to 2.2)	24	1.8	(1.6 to 2.0)	0.214
Stair ascension, s	26	4.9	(4.0 to 5.7)	24	4.8	(4.0 to 5.7)	0.884
WOMAC pain	26	16.3	(12.0 to 20.6)	24	16.9	(10.6 to 23.2)	0.866
WOMAC stiffness	26	31.8	(22.1 to 41.5)	24	24.7	(16.8 to 32.6)	0.254
WOMAC function	26	21.9	(17.0 to 26.8)	24	17.1	(12.2 to 22.0)	0.109

KEP= Knee extensor power at 180 $deg{\cdot}s^{-1}$, KFP= Knee flexor power at 180 $deg{\cdot}s^{-1}$, KET= Knee extensor torque at 60 $deg{\cdot}s^{-1}$, KFT= Knee flexor torque at 60 $deg{\cdot}s^{-1}$, CSA = Cross-sectional area, Asymmetrical muscle deficit= $\frac{Operated}{(Operated + Nonoperated)} * 100\%$, WOMAC= Western Ontario and McMaster University Osteoarthritis Index, WOMAC function= physical functional difficulty.

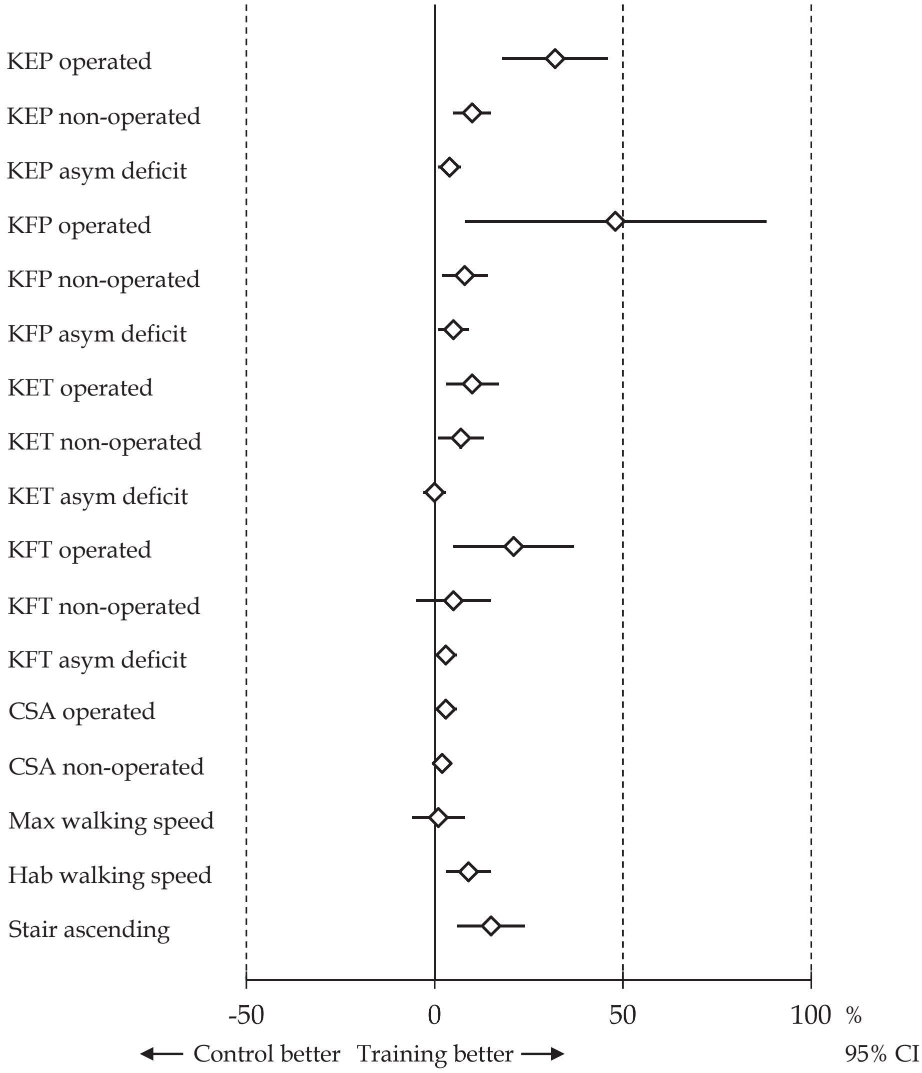

FIGURE 6 Training effects and 95% confidence intervals (CI) for knee extensor power at 180 deg·s^{-1} (KEP), knee flexor power at 180 deg·s^{-1} (KFP), knee extensor torque at 60 deg·s^{-1} (KET), knee flexor torque at 60 deg·s^{-1} (KFT), asymmetrical muscle deficit (asym deficit) and thigh muscle cross-sectional area (CSA) of operated and non-operated side, maximal (max) and habitual (hab) walking speed and stair ascension time between the training (n=25) and control groups (n=21). In asymmetrical muscle deficit a positive value means larger decrease in the training group (Study III).

Follow-up

At the follow-up (Study IV), a 32% (95%CI 10% to 53%) training effect in knee extensor power and 50% (9% to 90%) in knee flexor power of the operated side were still seen in the training group compared with the control group (ANCOVA p=0.008 and p=0.005, respectively; Figure 7). For absolute values see original paper IV. In knee extensor power of the non-operated side the training effect was 12% (0% to 25%) compared with controls (p=0.044). However, the training effect in knee flexor power of the non-operated side (p=0.058), in knee extensor and flexor asymmetrical power deficit (p=0.746 and p=0.750, respectively) was not maintained at follow-up.

Also in knee extensor and flexor torque of the operated side (p=0.640 and p=0.227, respectively), non-operated side (p=0.615 and p=0.350, respectively), in asymmetrical knee extensor and flexor torque deficit (p=0.166 and p=0.361, respectively) and in thigh muscle CSA of the operated and non-operated sides (p=0.486 and p=0.575, respectively), the training effect had disappeared at follow-up.

5.5.2 Mobility limitation

At baseline, there were no differences between the aquatic training group and the control group in maximal and habitual walking speeds or stair ascension time (Table 10). At baseline in the stair ascension test, three participants in the training group and one in the control group were unable to perform alternate stepping, and thus, used bipedal ascent.

After training, habitual walking speed increased 9% in the training group compared with the control group (ANCOVA p=0.005; Figure 6). However, maximal walking speed was not affected by training (p=0.532). Stair ascension time decreased 15% among the trainees compared to controls (p=0.006). At the follow-up, training-induced benefits in habitual walking speed and stair ascension had disappeared (p=0.414 and p=0.229, respectively).

5.5.3 Pain, stiffness and physical functional difficulty

At baseline, there were no differences between the aquatic training and control groups in the WOMAC physical functional difficulty, pain or stiffness scores (Table 10). The scores for physical functional difficulty (ANCOVA p=0.212), pain (p=0.352) and stiffness (p=0.097) in the operated knee were not affected by training. At the follow-up, no between-group differences were seen in physical functional difficulty (p=0.896), pain (p=0.152) or stiffness (p=0.485) scores.

a)

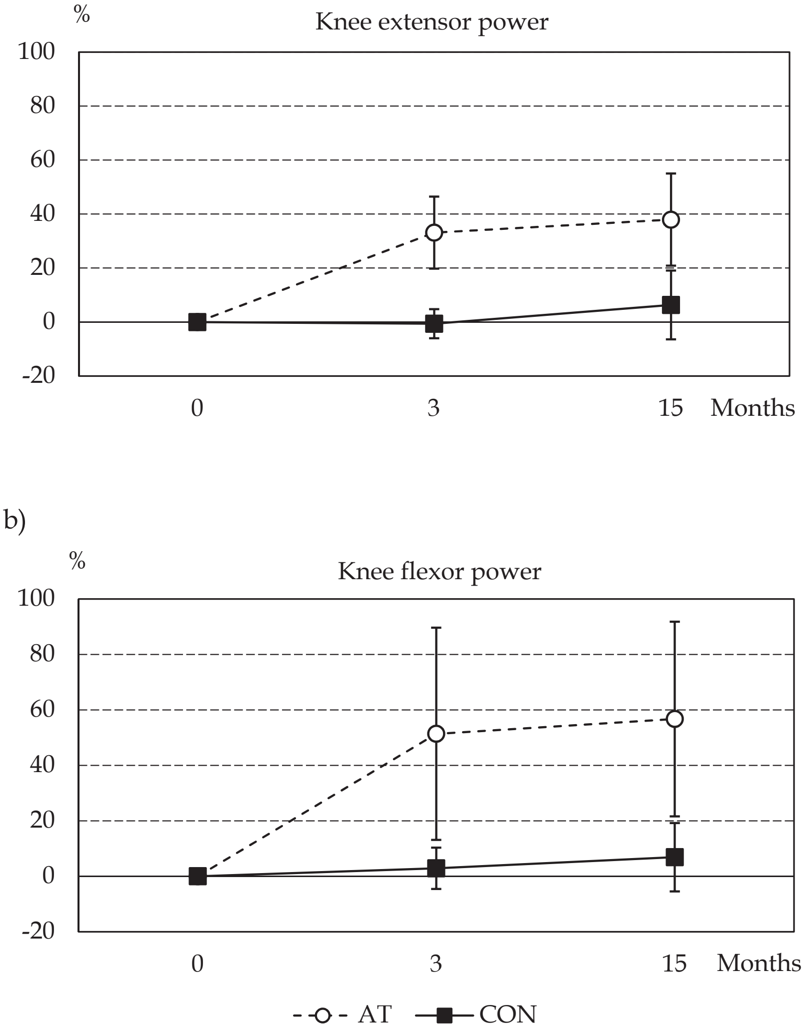

FIGURE 7 Percentage changes of isokinetic knee extensor power at 180 deg·s^{-1} (a) and knee flexor power at 180 deg·s^{-1} (b) of the operated side for training (AT; n=21) and control groups (CON; n=16) after 3 months of training (Study III) and at 12 months follow-up (15 months; Study IV).

6 DISCUSSION

The aim of this study was to investigate asymmetrical muscle deficit as an explanatory factor for mobility limitation in 50 to 75 year old persons with end-stage knee OA and with knee replacement. In addition, the effects of progressive aquatic resistance training on lower limb muscle function impairments, asymmetrical muscle deficit and mobility limitation, and the maintenance of training-induced benefits were studied.

Considerable asymmetrical muscle power, torque and muscle CSA deficits existed in the lower limbs of the participants with knee OA and with unilateral knee replacement. Both in participants with knee OA and with knee replacement, the asymmetrical knee extensor power deficit was associated with stair ascension, but not with walking speed. The present study showed that the aquatic resistance training was a feasible and effective mode of rehabilitation in participants with knee replacement. Three months of progressive aquatic resistance training decreased mobility limitation and asymmetrical muscle deficit in 55 to 75 year-old women and men after unilateral knee replacement. In addition, knee extensor and flexor power and torque, and thigh muscle CSA increased with training. Training-induced benefits in the knee extensor and flexor power remained one year after cessation of training. However, the training effects in mobility, muscle torque, asymmetrical muscle deficit and muscle CSA had disappeared at follow-up.

6.1 Asymmetrical muscle deficit and associations with mobility limitation

Asymmetrical muscle deficit in knee OA and knee replacement

In the present study, considerable muscle deficit in knee extensor and flexor power and torque existed both in participants with knee OA and with knee replacement, as most of the participants had less muscle power and torque on the affected side than on the non-affected side. In unilateral knee OA the asymmetrical muscle deficit is mainly generated by pain-related disuse of the lower limb (Suetta et al. 2007). Asymmetrical knee extensor power deficit in participants with knee OA (24%) was at a lower level than in two earlier studies in older persons with knee OA. However, the results are not fully comparable as the difference between the legs in those studies was calculated from the group mean values (Lamb & Frost 2003, Barker et al. 2012). Knee replacement surgery causes long wounds, considerable surgical trauma and long recovery times, and thus muscle impairments on the affected side may prevail. In this study, after common rehabilitation practice, the asymmetrical knee extensor power of the participants (23%) was still persistent. Present asymmetrical knee extensor power deficits were considerably larger than in previous studies in healthy older persons (12%) and at the same level as in mobility limited older persons (Carabello et al. 2010). On the other hand, 6 to 12 months after knee replacement, a 19% difference between the legs in knee extensor power (Lamb & Frost 2003) and even equivalent muscle power between the legs (Barker et al. 2012) have been reported. However, sufficient muscle power is extremely important as it is needed when performing demanding functional tasks, such as stair ascension (Bassey 1997), and also when recovering from a stumble (Thelen et al. 1996, Robinovitch et al. 2000, Thelen et al. 2000). Additionally, considerable asymmetrical knee extensor torque deficit was present in persons with knee OA and also after knee replacement, which confirms the previously reported deficit in muscle torque after unilateral disuse (Lorentzen et al. 1999, Gapeyeva et al. 2007). It can also be prolonged; the lower limb with the knee replacement has been shown to be significantly weaker than that of the healthy control subjects for as long as one year, and for even up to 13 years after the surgery (Huang et al. 1996, Walsh et al. 1998, Berth et al. 2002, Silva et al. 2003). Therefore, rehabilitation focusing on the muscle power and torque of the affected lower limb should be highlighted.

We also found remarkable asymmetrical muscle deficits in knee flexor power and torque of the participants with end-stage knee OA and also after knee replacement. It seems that the quite high asymmetrical power deficit in knee flexors noted presently has not been described in earlier studies. Whereas in knee flexor torque deficit, our results are in line with earlier studies in persons with knee OA and knee replacement (Lorentzen et al. 1999, Rossi et al. 2006). However, these substantial deficits would be important to take into consideration in rehabilitation because knee flexors provide stability for the knee joint during the movement, especially when the knee joint is unstable and painful (Schipplein & Andriacchi 1991), as in knee OA. Also, knee flexors are important for hip extension and forwards motion. Hence, the asymmetrical muscle deficit in knee flexors needs to be clarified in future studies, as they may also be important in preventing mobility limitation.

In addition to neural factors, muscle atrophy is an important mechanism underlying muscle weakness (Frontera et al. 2000). Previous studies have reported from 12 to 15% differences between the legs for quadriceps CSA in persons with severe knee OA (Petterson et al. 2008, Petterson et al. 2011). In our study the asymmetrical deficit in thigh CSA in participants with knee OA was somewhat smaller (5%). However, in the present study, the total thigh asymmetrical CSA deficit values were used and therefore the comparison to the previous studies is difficult. On average 10 months after knee replacement, we found 9% asymmetrical deficit in thigh muscle CSA. Earlier it has been shown that quadriceps CSA between the legs returns to the post-training level three months after knee replacement and it continues to decrease for at least one year after the surgery (Petterson et al. 2011). Overall, the present thigh CSA deficits in participants with knee OA and knee replacement may create a challenge for rehabilitation because increasing muscle CSA requires progressive strength training, which in part demands a long duration.

Associations with mobility limitation

As far as we know, this is the first study investigating the associations between asymmetrical muscle deficit and mobility in persons with end-stage knee OA or with knee replacement. The results of the present study suggested that maximal walking speed was not explained by asymmetrical muscle deficit. Whereas, both in participants with knee OA and knee replacement, the asymmetrical knee extensor power deficit turned out to be the most relevant asymmetrical muscle deficit variable associated with stair ascension. The results are in accordance with the previous study by Portegijs et al. (2008) who found that in women recovering from major surgery after hip fracture, a large power deficit was associated with limitations in stair climbing but not with walking speed. It would appear that because walking is a common functional task, the unaffected leg might be able to compensate for the problems of the affected leg. However, more demanding functional tasks, such as stair ascension, require more power and force production in the knee extensor muscles of both legs (Mizner & Snyder-Mackler 2005, Mizner et al. 2005a). On the contrary to our study conducted in clinical populations, an association between asymmetrical power deficit and walking speed in healthy older persons has also been reported (Portegijs et al. 2005). However, the association between asymmetrical muscle deficit and mobility limitation merits further investigation.

In accordance with earlier studies (Gur & Cakin 2003, Barker et al. 2004, Liikavainio et al. 2008, Kauppila et al. 2009), knee pain was severe in persons with end-stage knee OA. It is clinically known that severe knee pain is the most important disability-causing problem in persons with end-stage knee OA. As can be expected, a more intense knee pain was associated with more severe mobility limitation, explaining the variability in both maximal walking speed and stair ascension time, which have also been shown in earlier studies of knee OA (Gur & Cakin 2003, Barker et al. 2004, Liikavainio et al. 2008, Kauppila et al. 2009, McDaniel et al. 2011). In addition, an increased knee OA burden, which means that both knees were affected by knee OA, independently explained variability in stair ascension time in participants with knee OA. After successful knee replacement, the self-reported knee pain is usually lower and does not play an important role in mobility (Moffet et al. 2004, Escobar et al. 2007a, Escobar et al. 2007b, Bourne et al. 2010), which was also found in this study in participants with knee replacement.

Overall, it was quite expected that severe knee OA causes harmful effects on the affected side. However, it is quite surprising that equal asymmetrical muscle deficit can be found even months after knee replacement. However, the critical amount of asymmetrical muscle deficit is still not clear, and therefore patients should be directed towards intensive rehabilitation in clinical practice.

6.2 Effects of aquatic resistance training

Progressive resistance training is an effective method for increasing muscle strength and in decreasing mobility limitation in older persons (Latham et al. 2004). In this study the resistance training was conducted in a safe and comfortable but also effective training medium, water. The amount of resistance and thus the intensity of aquatic training are challenging to define in water. The intensity of training in previous studies conducted in water after knee replacement was either not defined (Liebs et al. 2012), described 'as tolerated' (Harmer et al. 2009) or the training was paced by a metronome (Rahmann et al. 2009). As well, additional resistance was not used during training. Our present training program is based on our previous study, in which we calculated movement velocities and drags during a similar training program conducted in healthy women (Pöyhönen et al. 2002). The progression of training was achieved by different sizes of resistance boots, which seemed to also add to the rating of perceived exertion (RPE) compared with the barefoot training. Based on RPE, the intensity during our resistance training was at a high level because the mean RPE value during training was 16, which is verbally located between 'hard' and 'very hard' on the RPE scale. Despite the high RPE levels during training, the progressive aquatic resistance training was a feasible mode of rehabilitation for participants with knee replacement as they were able to perform the training with high training compliance (98%) and a small drop-out rate (4%).

After aquatic resistance training, we found large training effects in the knee extensor power and in knee flexor power on the operated and the non-operated sides. As far as we know, there are no earlier RCTs investigating the effects of aquatic resistance training on muscle power in persons with knee replacement or with knee OA. Whereas, in persons with knee OA in very recent aquatic power training, which was conducted without additional resistance and did not include control group, positive results were found in stair ascension power (Segal & Wallace 2012). Also, in very recent fast-speed land-based training in persons with knee OA, some positive preliminary results in knee extensor muscle power have been found (Sayers et al. 2012). In the present study we found that the training effect in knee extensor and flexor power on the non-operated side was comparable to the training effects on fast torque production of earlier aquatic training interventions conducted with healthy adults and older persons (Pöyhönen et al. 2002, Takeshima et al. 2002). The asymmetrical deficits in knee extensor and flexor power also showed training effects in the present study. This was expected because the operated leg was weaker at the baseline and received 30% more training than the non-operated one. Parallel results have been reported earlier in persons with unilateral hip fracture, which showed positive training effects in asymmetrical leg extension power deficit after land-based strength training (Portegijs et al. 2008). In general, the training effect in muscle power was quite expected as our aquatic training was based on a fast movement velocity. In our earlier study, the peak angular velocities during resistance exercises in healthy women was 193 $deg \cdot s^{-1}$ during knee extension and 168 $deg \cdot s^{-1}$ in knee flexion (in men 210 and 174 $deg \cdot s^{-1}$, respectively) even with the largest resistance boot and doubled in the barefoot conditions (Pöyhönen et al. 2001a). Therefore, water is an excellent training medium to train muscle power, as it offers a possibility to perform each repetition with maximal effort and achieve the highest possible movement velocity and thus resistance.

The present training program increased the knee extensor and flexor torque of the weaker operated side, and also the knee extensor torque of the non-operated side. Further, the asymmetrical torque deficit was affected by training of knee flexors but not of knee extensors. Peak torque at the angular velocity of 60 $deg \cdot s^{-1}$ represent maximal torque production and the training program was in part designed to increase muscle torque, as the participants trained for four weeks with the large resistance boots. Previously, in healthy women the drag produced by knee exercises with large resistance boots has been on average 145 N in extension and 137 N in flexion (Pöyhönen et al. 2001a), which increased muscle torque even in healthy women (Pöyhönen et al. 2002). The respective values for men were 209 N and 176 N (Pöyhönen et al. 2001a). As far as we know, there is only one earlier study, which has investigated the effects of aquatic training on maximal muscle strength after knee replacement. After training they found increases in isometric hip abduction and knee extension muscle strength compared with the ward physiotherapy (Rahmann et al. 2009). In dry-land conditions the strength-training effects have not been studied after knee replacement in RCTs. It is also noticeable that the effects of resistance training on knee flexor muscle power or torque deficits have not been studied earlier in persons with knee OA or knee replacement, although knee flexors are known to provide stability for the knee joint during movements, especially when the knee joint is unstable and painful (Schipplein & Andriacchi 1991).

Muscle hypertrophy is one of the mechanisms underlying increasing muscle strength during training. However, the increase in muscle mass induced by resistance training is usually much less than the increase in muscle strength (Sipilä et al. 1996, Sipilä et al. 1997, Petrella et al. 2007). Accordingly, in this study, the training effect in muscle power and torque was larger than in muscle CSA, which indicates that also the neural factors improved by training.

However, the water produced enough resistance to increase the thigh muscle CSA of both legs compared to controls. A similar training program has earlier showed training effects in muscle CSA even in healthy women (Pöyhönen et al. 2002). As far as we know, there is a lack of earlier studies on aquatic training effects on muscle CSA in persons with lower limb problems. However, focusing the training on increasing muscle CSA is important as the muscle mass also has advantages other than increased force production. Muscle tissue acts as a metabolic store, as a vital source of heat, and protects the skeleton against falls (Parry-Billings et al. 1992).

Our aquatic resistance training had favorable effects on habitual walking speed and stair ascension time. However, maximal walking speed was not affected by training, which may be due to the relatively fast walking speed (1.9 $m \cdot s^{-1}$) of the participants at baseline. In studies with healthy older women (Tsourlou et al. 2006) and in persons with OA (Foley et al. 2003, Hinman et al. 2007), aquatic training with or without additional resistance has also shown favorable mobility effects. However, only two earlier studies have reported the effects of two to six weeks of aquatic exercise intervention compared with land-based rehabilitation (Harmer et al. 2009) or with ward physiotherapy (Rahmann et al. 2009) on mobility among people recovering from knee replacement surgery. In the recovery phase (<8 weeks postsurgery), mobility increased equally in the study groups with no between-group differences (Harmer et al. 2009, Rahmann et al. 2009). In addition to the positive changes in power, torque and CSA of the knee extensor and flexor muscles, our encouraging results in terms of mobility may be the result of the properties of water, which enable open kinetic chain exercises with natural rotations of the joints. Additionally, our training program included functional exercises such as walking, step-squat and exercises for the hip moving muscles, which in part may have increased mobility. Balance was not included in this study, however, water might offer a suitable medium for balance training as it helps to support the body in the upright position during the different balance challenging exercises (Elbar et al. 2013, Hale et al. 2012).

A few studies have been conducted on the effects of training on perceived mobility difficulty after knee replacement. Moffet et al. (2004) reported that an 8-week intensive functional land-based rehabilitation program after knee replacement decreased perceived physical functional difficulty (Moffet et al. 2004). No group differences in the physical functional difficulty were found after a 6-week water-based and land-based rehabilitation program commencing two weeks after knee replacement (Harmer et al. 2009). In this study, we found no effect on the self-reported physical functional difficulty compared with controls. This might be a result of the relatively long postoperative time and good health of the study population, who did not appear to have problems with simple daily tasks, such as lying in bed and sitting, even at baseline. In addition, training also had no effect on pain, which was quite expected because of the relatively small pain scores at baseline and this was also found after knee replacement in other studies (Moffet et al. 2004, Escobar et al. 2007a, Escobar et al. 2007b, Bourne et al. 2010).

As a summary, these observations suggest that aquatic resistance training induces versatile training effects in muscle function impairments and mobility limitation on average 10 months after knee replacement.

6.3 Maintenance of training-induced benefits

Aquatic resistance training decreased mobility limitation and muscle function impairments. However, it is even more important to know whether the training-induced benefits can be maintained after cessation of training. Notice must be taken for realizing that during a 12-month follow-up period, many confounding factors can affect on the results, which was also seen in our study. Three participants had their non-operated knee diagnosed with end-stage OA and replaced during the follow-up period, which is quite common after knee replacement surgery (Ritter et al. 1994, McMahon & Block 2003). Also at our follow-up, three participants had acute health problems and were not able to participate in the physical performance measurements. None of the participants continued aquatic resistance training after intervention. Additionally, the physical activity of the participants was maintained at the same level during follow-up.

In the present study the training effects in knee extensor and flexor power of the operated side, and in knee extensor power of the non-operated side were maintained at the post-training level for 12 months after cessation of training. The pain-free aquatic training environment might have encouraged patients to move with high movement velocity in everyday life and thus maintain their training-induced benefits in muscle power. However, the training effect in asymmetrical muscle power deficit had disappeared at follow-up. Previously, long-term effects of training on muscle strength in persons with knee replacement have been examined in some studies only. In the present study the training-induced benefits in muscle torque and asymmetrical torque deficit had disappeared at follow-up. As support for our results, six months after cessation of training the aquatic training effect on muscle strength had disappeared compared to the ward physiotherapy group (Rahmann et al. 2009). On the contrary, Petterson et al. (2009) found that their progressive land-based muscle strength training cohort with knee replacements was stronger than their non-training cohort 12 months after cessation of training. In this study, thigh muscle CSA in the training group was maintained at the post-training level, but the between-group difference disappeared. To our knowledge, no earlier studies in persons with knee replacement have reported on the maintenance of muscle CSA after resistance training. In healthy older adults, after land-based training, muscle CSA has been maintained (Ivey et al. 2000) or decreased (Taaffe et al. 2009) during a 6-month detraining period. However, it seems that the habitual physical activity of the participants, which did not include strength training, was not enough to maintain the present changes in maximal muscle torque and muscle CSA.

The training effect on mobility disappeared during the 12-month follow-up. A study in persons with fibromyalgia found parallel results after aquatic training, in which the positive changes in mobility were not maintained after the detraining period (Tomas-Carus et al. 2007). On the contrary, previous studies in persons with knee replacement have found further improvements in mobility from 3 to 12 months after cessation of training (Harmer et al. 2009, Petterson et al. 2009). However, the interventions were conducted in the recovery phase after surgery (Harmer et al. 2009) and a non-training control group was not included in these studies (Harmer et al. 2009, Petterson et al. 2009) and the training was conducted on dry land (Petterson et al. 2009). Our results may indicate that the mobility demands of daily living or the participants' habitual physical activity were not enough to maintain the training-induced changes in mobility.

6.4 Methodological considerations

The data of this study are based on two research projects conducted with participants that had unilateral end-stage knee OA and in participants with unilateral knee replacement. Both samples were population-based and therefore all of the patients awaiting knee replacement and the patients who had undergone knee replacement were invited to the study. To assure safe participation to the measurements and resistance training, the inclusion and exclusion criteria were quite tight, which somewhat weakens the generalization of the results. In cross-sectional analyses the results and 95% confidence intervals were clear and therefore the sample size is considered sufficient to study asymmetrical muscle deficit as an explanatory factor for mobility limitation. However, in the RCT the statistical power calculations assured that the sample size of the study was sufficient. Also, our participation percentage of 25% of the number needed to screen is greater than in the earlier studies investigating clinical populations in RCT studies, especially if frequent travelling is required (Chang et al. 2004, Frobell et al. 2007).

The calculations of asymmetrical muscle deficit were based on previous studies conducted on healthy older persons (Portegijs et al. 2005) and persons with hip fracture (Portegijs et al. 2008). We used the side-to-side difference divided by the value of the contralateral/non-operated side (Formulas 1 and 2) in cross-sectional analyses, because this approach is closer to that of earlier studies, which have calculated the difference from the group mean values. Then the comparison of the results is somewhat possible. In the RCT the asymmetrical muscle deficit was calculated as the value of the operated leg divided by the sum of both legs (Formula 3), which made the longitudinal comparisons of the results possible.

This study has the comprehensive measurements of asymmetrical deficits in knee extensor and flexor muscle power and torque, thigh muscle CSA, and mobility. The RCT study design allowed the effects of aquatic resistance training and the maintenance of training-induced benefits to be studied. Randomization was successful as the baseline characteristics of the training and control groups were comparable. Compared to the earlier aquatic training interventions targeted to patients with knee replacement, our intervention and follow-up were considerably longer. The participation rate for the intervention was high because the drop-out rate during the 3-month training period was only 8% and 16% during the entire 15-month follow-up. This strengthens the conclusions derived from the study.

The aquatic resistance training program was based on our earlier studies in healthy women (Pöyhönen et al. 2001a, Pöyhönen et al. 2002), which have used a similar training program and have also calculated the movement velocities and resistances produced during the exercises. We verbally encouraged the participants to exercise with maximal effort in each exercise. However, we do not know whether the subjects exercised to fatigue, even though they reported high RPE values during training. Progressive resistance training was well tolerated as the training group performed the training protocol with a high compliance and did not report any pain during training.

Study limitations

In the study population of the KNEE-OA study consisted of participants with mobility limitation induced by unilateral knee pain. The KNEE-REPLACEMENT study population consisted of relatively healthy and mobile participants with successful unilateral knee replacement. It is impossible to know whether during the recruitment processes people with larger mobility problems refused to participate, which might have reduced the variance in asymmetrical muscle deficits and in mobility problems. However, based on the inclusion criteria the results of this study can be generalized to relatively healthy older participants with painful unilateral end-stage knee OA and with successful unilateral knee replacement.

Participants of the RCT were not blinded to the study group, which is obvious in exercise studies. In addition, the assessors were not completely blinded to the study group in Studies II-IV, due to the infrastructure of the hospital. Unfortunately, we did not know the preoperative impairment or level of mobility limitation of the participants with knee replacement or the rehabilitation before the baseline measurements. However, the randomization, reduced this potential bias at least in part. In the RCT, it is possible that attending to the measurements motivated part of the control group to be physically more active, which may have caused some underestimation of the training effects. Unfortunately, we had only one follow-up measurement, which was conducted 12 months after cessation of training. In future studies, follow-up measurements after three and six months would offer interesting data about the maintenance of training effects upon mobility, muscle torque and muscle CSA.

The intensity of training was challenging to define. Even though the training program was based on previous study and the participants were encouraged to exercise with maximal effort, we do not know whether they did so. In addition, the training program was not started right after the surgery, which is the usual course in rehabilitation practice. Maximal torque and power was measured with an isokinetic dynamometer, and the participants did not report pain during the measurements. However, persons with OA may have pain or the fear of pain, which may alter the measured maximal physical performance. Thus, it is impossible to know whether the maximal torque and power results were underestimated in persons with knee OA.

The present study has well-defined datasets, including a randomized controlled trial and long follow-up study. In addition, this study has the comprehensive measurements of asymmetrical muscle deficit in lower limbs, and mobility. Therefore, this study adds new information to the earlier literature on asymmetrical muscle deficit associated with mobility limitation, and rehabilitation of people, who have had their knee replaced, with aquatic resistance training.

6.5 Implications and future directions

The present study suggests that asymmetrical muscle deficits in persons with knee OA and knee replacement are substantial, and these influence mobility limitation. Therefore, it is clear that rehabilitation before and after knee replacement is needed to prevent mobility limitation. Many previous studies have found positive effects of aquatic training in persons with knee OA in decreasing mobility limitation and increasing muscle strength compared with controls (Foley et al. 2003, Wang et al. 2011). Additionally, aquatic training is reported to be less painful than training on dry-land (Wyatt et al. 2001, Bartels et al. 2007, Lund et al. 2008, Silva et al. 2008, Gill et al. 2009, Wang et al. 2011), because the viscous resistance stops the movement immediately after cessation of force. Therefore, aquatic training might be optimal for resistance training in people with lower limb pain. However, previous studies have found more positive effects after land-based training than after aquatic training (Foley et al. 2003, Lund et al. 2008), but most of the studies have not used additional resistance during aquatic training. Therefore, it is not clear whether the high-intensity resistance training in water with additional resistance would be optimal in increasing muscle strength and mobility or could even be tolerated in severe lower limb OA. Also, it has been proposed that water immersion stimulates the vagus nerve (Perini et al. 1998), and thus may decrease the production of cytokines (Tracey 2007). Therefore, in addition to the increases in muscle power and torque, the training in water might also cause decreases in the inflammatory reaction and pain in knee OA. However, this hypothesis merits further investigation.

Also, targeting the training to the early phase of knee OA could prevent the progression of OA by maintaining muscle power and torque, and thus decrease the disease-induced pain through increased stability of the knee joint. Hence, the knee replacement surgery could even be postponed with intensive training. In addition, the preoperative aquatic resistance training in improving recovery after surgery merits further investigation. Regardless of the timing of training, water seems to be an effective but still comfortable training medium in which muscle power and mobility can be increased for people with painful joint problems.

Rehabilitation is needed after knee replacement surgery as well. The observations of the present study suggest that aquatic resistance training induces versatile training effects in muscle function impairments and mobility limitation on average 10 months after knee replacement. However, as suggested by previous studies (Harmer et al. 2009, Rahmann et al. 2009, Liebs et al. 2012) it would be optimal that the rehabilitation after knee replacement would be commenced earlier. Future studies are needed to find out whether progressive aquatic resistance training can be tolerated in the acute phase after knee replacement. In general, aquatic resistance training requires special infrastructure and equipment, and thus is not available for everybody. Therefore, it should be used as intensive training periods to rehabilitate persons with lower limb problems. However, further research needs to be done to find out the pre-eminent timing of aquatic resistance training after knee replacement in order to gain the best possible recovery of mobility. In addition, as the training-induced benefits in muscle torque, CSA and mobility had disappeared at the 12-month follow-up point, they should in future studies be followed at three and six months to find out the optimal interval for periodical training. Also, the cost-effectiveness of aquatic resistance training after knee replacement should be investigated.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings of the present study are as follows:

1. Substantial asymmetrical deficits in knee extensor and flexor muscle power, torque and CSA were found in persons with end-stage knee OA and in persons with knee replacement.
2. In persons with knee OA and in persons with knee replacement the asymmetrical knee extensor power deficit was associated with stair ascension time, but not with walking speed.
3. A progressive 3-month aquatic resistance training program designed to increase muscle power and torque, and thus mobility, was feasible and effective for persons with knee replacement. Muscle power, torque and CSA increased by training, especially on the operated side. In addition, the training decreased asymmetrical muscle deficit and mobility limitation.
4. The aquatic training-induced benefits in the knee extensor and flexor power in persons with knee replacement were maintained but the benefits in mobility, muscle torque, asymmetrical muscle deficit and muscle CSA had disappeared by 12-months after cessation of training.

In conclusion, the results of the study indicate that considerable asymmetrical muscle deficits in the lower limbs are present in persons with knee OA and knee replacement, and they have effects on mobility limitation. Aquatic resistance training offers an effective means to decrease mobility limitation by increasing muscle power, torque and CSA and by decreasing asymmetrical muscle deficit in the lower limbs. The training-induced benefits in muscle power may be maintained with regular physical activity alone, but this was not shown for mobility, muscle torque, asymmetrical muscle deficit and muscle CSA. The observations of the present study can be used in planning efficient interventions to prevent and rehabilitate mobility limitation related to knee OA and knee replacement.

YHTEENVETO (FINNISH SUMMARY)

Alaraajojen lihasten puoliero, liikkumiskyvyn rajoitus ja vesivastusharjoittelu polven nivelrikkoisilla henkilöillä

Polven nivelrikko on etenevä nivelsairaus, joka aiheuttaa vaikea-asteista kipua polvinivelessä. Tämä johtaa kivuliaan raajan käyttämättömyyteen ja edelleen liikkumiskyvyn rajoittumiseen. Polven tekonivelleikkaus on yleinen toimenpide, joka onnistuneesti vähentää kipua ja tästä seuraten parantaa vajaakuntoisuutta. Onnistuneen tekonivelleikkauksen jälkeen liikkumiskyky paranee, mutta kuitenkin vain harvoin se saavuttaa saman ikäisten terveiden ihmisten tason.

Liikkumiskyvyn rajoitusta polven nivelrikosta kärsivillä ja tekonivelleikatuilla voidaan selittää alaraajojen lihasten tehon ja vääntömomentin laskulla, jonka on todettu olevan suurempaa nivelrikosta kärsivässä raajassa. Lisäksi on huomionarvoista, että alaraajojen lihasten raajojen välinen puoliero saattaa osaltaan selittää liikkumiskyvyn rajoitusta. Tämä yhteys on aiemmin löydetty terveillä ikääntyneillä sekä lonkkamurtuman jälkeen, mutta polven nivelrikosta kärsivillä tai tekonivelleikatuilla yhteyttä ei ole tutkittu.

Koska polven nivelrikon seurauksena ja tekonivelleikkauksen jälkeen liikkumiskyvyn rajoitus ja lihasheikkous ovat huomattavan suuria, on kehitettävä tehokkaita harjoitusohjelmia ongelmien ennaltaehkäisyyn ja kuntouttamiseen. Vesi on tehokas ja kivuton harjoitusympäristö ihmisille, joiden harjoittelu saattaa olla hankalaa kuivalla maalla. Aiemmat satunnaistetut kontrolloidut kokeet ovat osoittaneet, että vesiharjoittelulla on positiivisia vaikutuksia terveiden ikääntyneiden ja kliinisten ryhmien toiminnan rajoituksiin. Akuuttivaiheessa tekonivelleikkauksen jälkeen ilman lisävastusta tapahtuvalla vesiharjoittelulla on löydetty positiivisia vaikutuksia liikkumiskykyyn. Ei kuitenkaan tiedetä, onko lisävastuksen kanssa toteutettu vesivastusharjoittelu tehokasta vähentämään liikkumiskyvyn rajoitusta tekonivelleikkauksen jälkeen. Lisäksi ei tiedetä säilyykö harjoitusvaikutus harjoittelun lopettamisen jälkeen.

Tässä tutkimuksessa selvitettiin polven nivelrikosta kärsivien ja polven tekonivelleikattujen henkilöiden alaraajojen lihasten puolieroa sekä sen yhteyttä liikkumiskykyyn. Lisäksi tutkittiin kolmen kuukauden mittaisen vesivastusharjoittelun vaikutusta liikkumiskykyyn, alaraajojen lihasten tehoon, vääntömomenttiin ja lihasten poikkipinta-alaan sekä puolieroon. Harjoitusvaikutusten pysyvyyttä tarkasteltiin 12 kuukautta harjoittelun päättymisen jälkeen.

Tutkimuksessa käytettiin kahta tutkimusaineistoa. KNEE-OA tutkimukseen osallistui 43 polven nivelrikosta kärsivää 50-75-vuotiasta naista ja miestä, jotka olivat Kymenlaakson keskussairaalan leikkausjonossa polven tekonivelleikkaukseen. KNEE-REPLACEMENT tutkimusprojektiin osallistui 50 Kymenlaakson keskussairaalassa polven tekonivelleikattua 55-75-vuotiasta naista ja miestä. Tutkittavien liikkumiskyky sekä alaraajojen lihasten teho, vääntömomentti ja poikkipinta-ala mitattiin. Lisäksi lihasten puoliero laskettiin ja itsearvioitu toimintakyvyn vaikeus arvioitiin kyselylomakkeen avulla. Polven tekonivelleikatut tutkittavat satunnaistettiin koe- (n=26) ja kontrolliryhmiin (n=24). Koeryhmä osallistui kolmen kuukauden mittaiseen progressiiviseen vastuskenkien avulla toteutettuun vesivastusharjoitteluun, jonka tarkoituksena oli lisätä alaraajojen lihasten tehoa ja vääntömomenttia sekä vähentää puolieroa ja sitä kautta parantaa liikkumiskykyä. Harjoitusvaikutusten pysyvyyttä tutkittiin 12 kuukautta harjoittelun päättymisen jälkeen.

Tutkimuksen tulokset osoittivat, että polven nivelrikosta kärsivien ja polven tekonivelleikattujen polven ojentaja- ja koukistajalihasten alaraajojen välinen puoliero oli suuri. Lisäksi polven ojennustehon puoliero oli yhteydessä portaiden nousuun käytettyyn aikaan. Kokeellinen tutkimus osoitti, että pienryhmäharjoitteluna toteutetulla progressiivisella vesivastusharjoittelulla voidaan parantaa polven tekonivelleikattujen liikkumiskykyä. Lisäksi vesiharjoittelu lisäsi merkitsevästi alaraajojen lihasten tehoa, vääntömomenttia ja poikkipinta-alaa sekä vähensi puolieroa. Saavutetut tulokset lihastehossa säilyivät 12 kuukautta harjoittelun päättymisen jälkeen. Tutkittavien tavanomainen fyysinen aktiivisuus ei kuitenkaan ollut riittävä, jotta harjoitusvaikutus liikkumiskyvyssä, vääntömomentissa, lihasten poikkipinta-alassa ja puolierossa olisi säilynyt seuranta-ajan.

Yhteenvetona voidaan todeta, että alaraajojen lihasten puoliero polven nivelrikkoisilla ja tekonivelleikatuilla on huomattavan suurta ja tulisi ottaa huomioon liikkumiskyvyn ongelmien kuntoutuksessa. Vesivastusharjoittelun avulla voidaan parantaa polven tekonivelleikattujen liikkumiskykyä, lihastehoa, vääntömomenttia ja lihasmassaa sekä vähentää puolieroa. Näistä tavanomaisen fyysisen aktiivisuuden avulla harjoitusvaikutus voidaan säilyttää ainoastaan lihastehossa. Tämän tutkimuksen tuloksia voidaan hyödyntää polven nivelrikosta kärsivien ja tekonivelleikattujen liikkumisvaikeuksia ennaltaehkäisevien ja kuntouttavien interventioiden suunnittelussa. Lisätutkimuksia kuitenkin tarvitaan selvittämään, mikä on optimaalinen ajoitus progressiivisen vesivastuskuntoutuksen toteuttamiselle polven tekonivelleikkauksen jälkeen.

REFERENCES

Ackroyd, C. E. 2003. Medial compartment arthroplasty of the knee. The Journal of Bone and Joint Surgery. British volume 85 (7), 937-942.

Alexander, N. B., Dengel, D. R., Olson, R. J. & Krajewski, K. M. 2003. Oxygen-uptake (VO2) kinetics and functional mobility performance in impaired older adults. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 58 (8), 734-739.

Altman, R., Asch, E., Bloch, D., Bole, G., Borenstein, D., Brandt, K., Christy, W., Cooke, T. D., Greenwald, R. & Hochberg, M. 1986. Development of criteria for the classification and reporting of osteoarthritis. Classification of osteoarthritis of the knee. Diagnostic and Therapeutic Criteria Committee of the American Rheumatism Association. Arthritis and Rheumatism 29 (8), 1039-1049.

Anchuela, J., Gomez-Pellico, L., Ferrer-Blanco, M., Slocker, M. & Rodriguez, R. 2001. Muscular function and bone mass after knee arthroplasty. International Orthopaedics 25 (4), 253-256.

Arokoski, J. P., Jurvelin, J. S., Väätäinen, U. & Helminen, H. J. 2000. Normal and pathological adaptations of articular cartilage to joint loading. Scandinavian Journal of Medicine & Science in Sports 10 (4), 186-198.

Arokoski, J. P., Lammi, M. J., Hyttinen, M. M., Kiviranta, I., Parkkinen, J. J., Jurvelin, J. S., Tammi, M. I. & Helminen, H. J. 2001. Nivelrikon etiopatogeneesi. Duodecim 117, 1617-1626.

Arokoski, J., Manninen, P., Kröger, H., Heliövaara, M., Nykyri, E. & Impivaara, O. 2007. Hip and knee pain and osteoarthritis. In L. Kaila-Kangas (Ed.) Musculoskeletal Disorders and Diseases in Finland. Results of the Health 2000 Survey. Publications of the National Public Health Institute B25/2007, 37-41.

Avramidis, K., Karachalios, T., Popotonasios, K., Sacorafas, D., Papathanasiades, A. A. & Malizos, K. N. 2011. Does electric stimulation of the vastus medialis muscle influence rehabilitation after total knee replacement? Orthopedics 34 (3), 175. doi: 10.3928/01477447-20110124-06.

Avramidis, K., Strike, P. W., Taylor, P. N. & Swain, I. D. 2003. Effectiveness of electric stimulation of the vastus medialis muscle in the rehabilitation of patients after total knee arthroplasty. Archives of Physical Medicine and Rehabilitation 84 (12), 1850-1853.

Barker, K., Lamb, S. E., Toye, F., Jackson, S. & Barrington, S. 2004. Association between radiographic joint space narrowing, function, pain and muscle power in severe osteoarthritis of the knee. Clinical Rehabilitation 18 (7), 793-800.

Barker, K. L., Jenkins, C., Pandit, H. & Murray, D. 2012. Muscle power and function two years after unicompartmental knee replacement. The Knee 19 (4), 360-364.

Bartels, E. M., Lund, H., Hagen, K. B., Dagfinrud, H., Christensen, R. & Danneskiold-Samsoe, B. 2007. Aquatic exercise for the treatment of knee and hip osteoarthritis. Cochrane Database of Systematic Reviews 4, CD005523.

Bassey, E. J. 1997. Measurement of muscle strength and power. Muscle & Nerve. Supplement 5, S44-S46.

Bassey, E. J., Fiatarone, M. A., O'Neill, E. F., Kelly, M., Evans, W. J. & Lipsitz, L. A. 1992. Leg extensor power and functional performance in very old men and women. Clinical Science (London) 82 (3), 321-327.

Bean, J. F., Kiely, D. K., Herman, S., Leveille, S. G., Mizer, K., Frontera, W. R. & Fielding, R. A. 2002. The relationship between leg power and physical performance in mobility-limited older people. Journal of the American Geriatrics Society 50 (3), 461-467.

Bean, J. F., Kiely, D. K., LaRose, S., Goldstein, R., Frontera, W. R. & Leveille, S. G. 2010. Are changes in leg power responsible for clinically meaningful improvements in mobility in older adults? Journal of the American Geriatrics Society 58 (12), 2363-2368.

Bean, J. F., Leveille, S. G., Kiely, D. K., Bandinelli, S., Guralnik, J. M. & Ferrucci, L. 2003. A comparison of leg power and leg strength within the InCHIANTI study: Which influences mobility more? The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 58 (8), 728-733.

Becker, B. E. 2004. Biophysiologic Aspects of Hydrotherapy. In A. J. Cole & B. E. Becker (Eds.) Comprehensive Aquatic Therapy. (Second edition) Oxford: Elsevier Inc., 19-56.

Beissner, K. L., Collins, J. E. & Holmes, H. 2000. Muscle force and range of motion as predictors of function in older adults. Physical Therapy 80 (6), 556-563.

Bellamy, N., Buchanan, W. W., Goldsmith, C. H., Campbell, J. & Stitt, L. W. 1988. Validation study of WOMAC: A health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. The Journal of Rheumatology 15 (12), 1833-1840.

Berman, A. T., Bosacco, S. J. & Israelite, C. 1991. Evaluation of total knee arthroplasty using isokinetic testing. Clinical Orthopaedics and Related Research (271), 106-113.

Berth, A., Urbach, D. & Awiszus, F. 2002. Improvement of voluntary quadriceps muscle activation after total knee arthroplasty. Archives of Physical Medicine and Rehabilitation 83 (10), 1432-1436.

Bohannon, R. W. 1997. Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. Age and Ageing 26 (1), 15-19.

Borg, G. 1998. Borg's Perceived Exertion and Pain Scales. Champaign, IL: Human Kinetics.

Bourne, R. B., Chesworth, B. M., Davis, A. M., Mahomed, N. N. & Charron, K. D. 2010. Patient satisfaction after total knee arthroplasty: Who is satisfied and who is not? Clinical Orthopaedics and Related Research 468 (1), 57-63.

Brandt, K. D., Radin, E. L., Dieppe, P. A. & van de Putte, L. 2006. Yet more evidence that osteoarthritis is not a cartilage disease. Annals of the Rheumatic Diseases 65 (10), 1261-1264.

Buckwalter, J. A. 1995. Osteoarthritis and articular cartilage use, disuse, and abuse: Experimental studies. The Journal of Rheumatology. Supplement 43, 13-15.

Buckwalter, J. A. & Mankin, H. J. 1998. Articular cartilage: Degeneration and osteoarthritis, repair, regeneration, and transplantation. Instructional Course Lectures 47, 487-504.

Buszewicz, M., Rait, G., Griffin, M., Nazareth, I., Patel, A., Atkinson, A., Barlow, J. & Haines, A. 2006. Self management of arthritis in primary care: Randomised controlled trial. BMJ 333 (7574), 879.

Carabello, R. J., Reid, K. F., Clark, D. J., Phillips, E. M. & Fielding, R. A. 2010. Lower extremity strength and power asymmetry assessment in healthy and mobility-limited populations: Reliability and association with physical functioning. Aging Clinical and Experimental Research 22 (4), 324-329.

Chang, B. H., Hendricks, A. M., Slawsky, M. T. & Locastro, J. S. 2004. Patient recruitment to a randomized clinical trial of behavioral therapy for chronic heart failure. BMC Medical Research Methodology 4, 8.

Christensen, R., Bartels, E. M., Astrup, A. & Bliddal, H. 2007. Effect of weight reduction in obese patients diagnosed with knee osteoarthritis: A systematic review and meta-analysis. Annals of the Rheumatic Diseases 66 (4), 433-439.

Cochrane, T., Davey, R. C. & Matthes Edwards, S. M. 2005. Randomised controlled trial of the cost-effectiveness of water-based therapy for lower limb osteoarthritis. Health Technology Assessment 9 (31), iii-iv, ix-xi, 1-114.

Colado, J. C., Garcia-Masso, X., Gonzalez, L. M., Triplett, N. T., Mayo, C. & Merce, J. 2010. Two-leg squat jumps in water: An effective alternative to dry land jumps. International Journal of Sports Medicine 31 (2), 118-122.

Colado, J. C., Tella, V. & Triplett, N. T. 2008. A method for monitoring intensity during aquatic resistance exercises. Journal of Strength and Conditioning Research 22 (6), 2045-2049.

Colado, J. C., Tella, V., Triplett, N. T. & Gonzalez, L. M. 2009a. Effects of a short-term aquatic resistance program on strength and body composition in fit young men. Journal of Strength and Conditioning Research 23 (2), 549-559.

Colado, J. C., Triplett, N. T., Tella, V., Saucedo, P. & Abellan, J. 2009b. Effects of aquatic resistance training on health and fitness in postmenopausal women. European Journal of Applied Physiology 106 (1), 113-122.

Cunningham, D. A., Rechnitzer, P. A., Pearce, M. E. & Donner, A. P. 1982. Determinants of self-selected walking pace across ages 19 to 66. Journal of Gerontology 37 (5), 560-564.

Das, S. K. & Farooqi, A. 2008. Osteoarthritis. Best Practice & Research. Clinical Rheumatology 22 (4), 657-675.

Dillon, C. F., Rasch, E. K., Gu, Q. & Hirsch, R. 2006. Prevalence of knee osteoarthritis in the United States: Arthritis data from the Third National Health and Nutrition Examination Survey 1991-94. The Journal of Rheumatology 33 (11), 2271-2279.

Elbar, O., Tzedek, I., Vered, E., Shvarth, G., Friger, M. & Melzer, I. 2013. A water-based training program that includes perturbation exercises improves speed of voluntary stepping in older adults: A randomized controlled cross-over trial. Archives of Gerontology and Geriatrics 56 (1), 134-140.

Enoka, R. M. 2002. Neuromechanics of Human Movement. (3rd edition) United States of America: Human Kinetics.

Escobar, A., Quintana, J. M., Bilbao, A., Arostegui, I., Lafuente, I. & Vidaurreta, I. 2007a. Responsiveness and clinically important differences for the WOMAC and SF-36 after total knee replacement. Osteoarthritis and Cartilage 15 (3), 273-280.

Escobar, A., Quintana, J. M., Bilbao, A., Azkarate, J., Guenaga, J. I., Arenaza, J. C. & Gutierrez, L. F. 2007b. Effect of patient characteristics on reported outcomes after total knee replacement. Rheumatology (Oxford, England) 46 (1), 112-119.

Felson, D. E. 2003. Epidemiology of osteoarthritis. In K. Brandt, M. Doherty & S. Lohmander (Eds.) Osteoarthritis. (Second edition) Oxford: Oxford University Press, 9-16.

Felson, D. T. 2004. An update on the pathogenesis and epidemiology of osteoarthritis. Radiologic Clinics of North America 42 (1), 1-9.

Felson, D. T., Naimark, A., Anderson, J., Kazis, L., Castelli, W. & Meenan, R. F. 1987. The prevalence of knee osteoarthritis in the elderly. The Framingham Osteoarthritis Study. Arthritis and Rheumatism 30 (8), 914-918.

Finch, E., Walsh, M., Thomas, S. G. & Woodhouse, L. J. 1998. Functional ability perceived by individuals following total knee arthroplasty compared to age-matched individuals without knee disability. The Journal of Orthopaedic and Sports Physical Therapy 27 (4), 255-263.

Fitzgerald, J. D., Orav, E. J., Lee, T. H., Marcantonio, E. R., Poss, R., Goldman, L. & Mangione, C. M. 2004. Patient quality of life during the 12 months following joint replacement surgery. Arthritis and Rheumatism 51 (1), 100-109.

Foley, A., Halbert, J., Hewitt, T. & Crotty, M. 2003. Does hydrotherapy improve strength and physical function in patients with osteoarthritis--A randomised controlled trial comparing a gym based and a hydrotherapy based strengthening programme. Annals of the Rheumatic Diseases 62 (12), 1162-1167.

Fransen, M., Nairn, L., Winstanley, J., Lam, P. & Edmonds, J. 2007. Physical activity for osteoarthritis management: a randomized controlled clinical trial evaluating hydrotherapy or Tai Chi classes. Arthritis and Rheumatism 57 (3), 407-414.

Frobell, R. B., Lohmander, L. S. & Roos, E. M. 2007. The challenge of recruiting patients with anterior cruciate ligament injury of the knee into a randomized clinical trial comparing surgical and non-surgical treatment. Contemporary Clinical Trials 28 (3), 295-302.

Frontera, W. R., Hughes, V. A., Fielding, R. A., Fiatarone, M. A., Evans, W. J. & Roubenoff, R. 2000. Aging of skeletal muscle: A 12-yr longitudinal study. Journal of Applied Physiology 88 (4), 1321-1326.

Gapeyeva, H., Buht, N., Peterson, K., Ereline, J., Haviko, T. & Pääsuke, M. 2007. Quadriceps femoris muscle voluntary isometric force production and relaxation characteristics before and 6 months after unilateral total knee arthroplasty in women. Knee surgery, Sports Traumatology, Arthroscopy 15 (2), 202-211.

Gill, S. D., McBurney, H. & Schulz, D. L. 2009. Land-based versus pool-based exercise for people awaiting joint replacement surgery of the hip or knee: Results of a randomized controlled trial. Archives of Physical Medicine and Rehabilitation 90 (3), 388-394.

Gur, H. & Cakin, N. 2003. Muscle mass, isokinetic torque, and functional capacity in women with osteoarthritis of the knee. Archives of Physical Medicine and Rehabilitation 84 (10), 1534-1541.

Hale, L. A., Waters, D. & Herbison, P. 2012. A randomized controlled trial to investigate the effects of water-based exercise to improve falls risk and physical function in older adults with lower-extremity osteoarthritis. Archives of Physical Medicine and Rehabilitation 93 (1), 27-34.

Hamel, K. A. & Cavanagh, P. R. 2004. Stair performance in people aged 75 and older. Journal of the American Geriatrics Society 52 (4), 563-567.

Haq, I., Murphy, E. & Dacre, J. 2003. Osteoarthritis. Postgraduate Medical Journal 79 (933), 377-383.

Harmer, A. R., Naylor, J. M., Crosbie, J. & Russell, T. 2009. Land-based versus water-based rehabilitation following total knee replacement: A randomized, single-blind trial. Arthritis and Rheumatism 61 (2), 184-191.

Hartmann, S. & Huch, R. 2005. Response of pregnancy leg edema to a single immersion exercise session. Acta Obstetricia et Gynecologica Scandinavica 84 (12), 1150-1153.

Hawker, G. A. 2006. Who, when, and why total joint replacement surgery? The patient's perspective. Current Opinion in Rheumatology 18 (5), 526-530.

Hinman, R. S., Heywood, S. E. & Day, A. R. 2007. Aquatic physical therapy for hip and knee osteoarthritis: Results of a single-blind randomized controlled trial. Physical Therapy 87 (1), 32-43.

Holla, J. F., van der Leeden, M., Knol, D. L., Peter, W. F., Roorda, L. D., Lems, W. F., Wesseling, J., Steultjens, M. P. & Dekker, J. 2012. Avoidance of activities in early symptomatic knee osteoarthritis: Results from the CHECK cohort. Annals of Behavioral Medicine 44 (1), 33-42.

Huang, C. H., Cheng, C. K., Lee, Y. T. & Lee, K. S. 1996. Muscle strength after successful total knee replacement: A 6- to 13-year followup. Clinical Orthopaedics and Related Research (328), 147-154.

Hurley, M. V. 1999. The role of muscle weakness in the pathogenesis of osteoarthritis. Rheumatic Diseases Clinics of North America 25 (2), 283-298.

Ikeda, S., Tsumura, H. & Torisu, T. 2005. Age-related quadriceps-dominant muscle atrophy and incident radiographic knee osteoarthritis. Journal of Orthopaedic Science 10 (2), 121-126.

Ivey, F. M., Tracy, B. L., Lemmer, J. T., NessAiver, M., Metter, E. J., Fozard, J. L. & Hurley, B. F. 2000. Effects of strength training and detraining on muscle quality: Age and gender comparisons. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 55 (3), B152-B157; discussion B158-B159.

Jette, A. M. 2009. Toward a common language of disablement. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 64 (11), 1165-1168.

Johnson, A. W., Myrer, J. W., Hunter, I., Feland, J. B., Hopkins, J. T., Draper, D. O. & Eggett, D. 2010. Whole-body vibration strengthening compared to traditional strengthening during physical therapy in individuals with total knee arthroplasty. Physiotherapy Theory and Practice 26 (4), 215-225.

Jones, D. L., Westby, M. D., Greidanus, N., Johanson, N. A., Krebs, D. E., Robbins, L., Rooks, D. S. & Brander, V. 2005. Update on hip and knee arthroplasty: Current state of evidence. Arthritis and Rheumatism 53 (5), 772-780.

Jordan, J. M., Helmick, C. G., Renner, J. B., Luta, G., Dragomir, A. D., Woodard, J., Fang, F., Schwartz, T. A., Abbate, L. M., Callahan, L. F., Kalsbeek, W. D. & Hochberg, M. C. 2007. Prevalence of knee symptoms and radiographic and symptomatic knee osteoarthritis in African Americans and Caucasians: The Johnston County Osteoarthritis Project. The Journal of Rheumatology 34 (1), 172-180.

Katsura, Y., Yoshikawa, T., Ueda, S. Y., Usui, T., Sotobayashi, D., Nakao, H., Sakamoto, H., Okumoto, T. & Fujimoto, S. 2010. Effects of aquatic exercise training using water-resistance equipment in elderly. European Journal of Applied Physiology 108 (5), 957-964.

Kauppila, A. M., Kyllönen, E., Mikkonen, P., Ohtonen, P., Laine, V., Siira, P., Niinimäki, J. & Arokoski, J. P. 2009. Disability in end-stage knee osteoarthritis. Disability and Rehabilitation 31 (5), 370-380.

Kauppila, A. M., Kyllönen, E., Ohtonen, P., Hämäläinen, M., Mikkonen, P., Laine, V., Siira, P., Mäki-Heikkilä, P., Sintonen, H., Leppilahti, J. & Arokoski, J. P. 2010. Multidisciplinary rehabilitation after primary total knee arthroplasty: A randomized controlled study of its effects on functional capacity and quality of life. Clinical Rehabilitation 24 (5), 398-411.

Kellgren, J. H. & Lawrence, J. S. 1957. Radiological assessment of osteoarthrosis. Annals of the Rheumatic Diseases 16 (4), 494-502.

Knee and hip osteoarthritis: Current Care guideline. 2012. Working group set up by the Finnish Medical Society Duodecim and the Finnish Orthopedic

Society. Helsinki: Finnish Medical Society Duodecim. Referred 8 January 2013. Available online at: www.kaypahoito.fi.

Lamb, S. E. & Frost, H. 2003. Recovery of mobility after knee arthroplasty: Expected rates and influencing factors. The Journal of Arthroplasty 18 (5), 575-582.

Lamb, S. E., Morse, R. E. & Evans, J. G. 1995. Mobility after proximal femoral fracture: The relevance of leg extensor power, postural sway and other factors. Age and Ageing 24 (4), 308-314.

LaRoche, D. P., Millett, E. D. & Kralian, R. J. 2011. Low strength is related to diminished ground reaction forces and walking performance in older women. Gait & Posture 33 (4), 668-672.

LaStayo, P. C., Meier, W., Marcus, R. L., Mizner, R., Dibble, L. & Peters, C. 2009. Reversing muscle and mobility deficits 1 to 4 years after TKA: A pilot study. Clinical Orthopaedics and Related Research 467 (6), 1493-1500.

Latham, N. K., Bennett, D. A., Stretton, C. M. & Anderson, C. S. 2004. Systematic review of progressive resistance strength training in older adults. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 59 (1), 48-61.

Lauretani, F., Russo, C. R., Bandinelli, S., Bartali, B., Cavazzini, C., Di Iorio, A., Corsi, A. M., Rantanen, T., Guralnik, J. M. & Ferrucci, L. 2003. Age-associated changes in skeletal muscles and their effect on mobility: An operational diagnosis of sarcopenia. Journal of Applied Physiology 95 (5), 1851-1860.

Lawrence, R. C., Felson, D. T., Helmick, C. G., Arnold, L. M., Choi, H., Deyo, R. A., Gabriel, S., Hirsch, R., Hochberg, M. C., Hunder, G. G., Jordan, J. M., Katz, J. N., Kremers, H. M., Wolfe, F. & National Arthritis Data Workgroup 2008. Estimates of the prevalence of arthritis and other rheumatic conditions in the United States. Part II. Arthritis and Rheumatism 58 (1), 26-35.

Lewek, M. D., Rudolph, K. S. & Snyder-Mackler, L. 2004. Quadriceps femoris muscle weakness and activation failure in patients with symptomatic knee osteoarthritis. Journal of Orthopaedic Research 22 (1), 110-115.

Liebs, T. R., Herzberg, W., Ruther, W., Haasters, J., Russlies, M., Hassenpflug, J. & Multicenter Arthroplasty Aftercare Project 2012. Multicenter randomized controlled trial comparing early versus late aquatic therapy after total hip or knee arthroplasty. Archives of Physical Medicine and Rehabilitation 93 (2), 192-199.

Liikavainio, T., Lyytinen, T., Tyrväinen, E., Sipilä, S. & Arokoski, J. P. 2008. Physical function and properties of quadriceps femoris muscle in men with knee osteoarthritis. Archives of Physical Medicine and Rehabilitation 89 (11), 2185-2194.

Lim, J. Y., Tchai, E. & Jang, S. N. 2010. Effectiveness of aquatic exercise for obese patients with knee osteoarthritis: A randomized controlled trial. PM & R : The Journal of Injury, Function, and Rehabilitation 2 (8), 723-31; quiz 793.

Lorentzen, J. S., Petersen, M. M., Brot, C. & Madsen, O. R. 1999. Early changes in muscle strength after total knee arthroplasty. A 6-month follow-up of 30 knees. Acta Orthopaedica Scandinavica 70 (2), 176-179.

Lund, H., Weile, U., Christensen, R., Rostock, B., Downey, A., Bartels, E. M., Danneskiold-Samsoe, B. & Bliddal, H. 2008. A randomized controlled trial of aquatic and land-based exercise in patients with knee osteoarthritis. Journal of Rehabilitation Medicine 40 (2), 137-144.

Malatesta, D., Simar, D., Dauvilliers, Y., Candau, R., Ben Saad, H., Prefaut, C. & Caillaud, C. 2004. Aerobic determinants of the decline in preferred walking speed in healthy, active 65- and 80-year-olds. European Journal of Physiology 447 (6), 915-921.

Marsh, A. P., Rejeski, W. J., Lang, W., Miller, M. E. & Messier, S. P. 2003. Baseline balance and functional decline in older adults with knee pain: The Observational Arthritis Study in Seniors. Journal of the American Geriatrics Society 51 (3), 331-339.

Martin, S. D., Scott, R. D. & Thornhill, T. S. 1998. Current concepts of total knee arthroplasty. The Journal of Orthopaedic and Sports Physical Therapy 28 (4), 252-261.

McDaniel, G., Renner, J. B., Sloane, R. & Kraus, V. B. 2011. Association of knee and ankle osteoarthritis with physical performance. Osteoarthritis and Cartilage 19 (6), 634-638.

McKnight, P. E., Kasle, S., Going, S., Villanueva, I., Cornett, M., Farr, J., Wright, J., Streeter, C. & Zautra, A. 2010. A comparison of strength training, self-management, and the combination for early osteoarthritis of the knee. Arthritis Care & Research 62 (1), 45-53.

McMahon, M. & Block, J. A. 2003. The risk of contralateral total knee arthroplasty after knee replacement for osteoarthritis. The Journal of Rheumatology 30 (8), 1822-1824.

Meier, W., Mizner, R. L., Marcus, R. L., Dibble, L. E., Peters, C. & Lastayo, P. C. 2008. Total knee arthroplasty: Muscle impairments, functional limitations, and recommended rehabilitation approaches. The Journal of Orthopaedic and Sports Physical Therapy 38 (5), 246-256.

Menz, H. B., Morris, M. E. & Lord, S. R. 2005. Foot and ankle characteristics associated with impaired balance and functional ability in older people. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 60 (12), 1546-1552.

Mizner, R. L., Petterson, S. C. & Snyder-Mackler, L. 2005a. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. The Journal of Orthopaedic and Sports Physical Therapy 35 (7), 424-436.

Mizner, R. L., Petterson, S. C., Stevens, J. E., Axe, M. J. & Snyder-Mackler, L. 2005b. Preoperative quadriceps strength predicts functional ability one year after total knee arthroplasty. The Journal of Rheumatology 32 (8), 1533-1539.

Mizner, R. L., Petterson, S. C., Stevens, J. E., Vandenborne, K. & Snyder-Mackler, L. 2005c. Early quadriceps strength loss after total knee arthroplasty. The contributions of muscle atrophy and failure of voluntary muscle activation. The Journal of Bone and Joint Surgery. American volume 87 (5), 1047-1053.

Mizner, R. L. & Snyder-Mackler, L. 2005. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. Journal of Orthopaedic Research 23 (5), 1083-1090.

Moe, R. H., Fernandes, L. & Osteras, N. 2012. Daily use of a cane for two months reduced pain and improved function in patients with knee osteoarthritis. Journal of Physiotherapy 58 (2), 128. doi: 10.1016/S1836-9553(12)70094-2.

Moffet, H., Collet, J. P., Shapiro, S. H., Paradis, G., Marquis, F. & Roy, L. 2004. Effectiveness of intensive rehabilitation on functional ability and quality of life after first total knee arthroplasty: A single-blind randomized controlled trial. Archives of Physical Medicine and Rehabilitation 85 (4), 546-556.

Morie, M., Reid, K. F., Miciek, R., Lajevardi, N., Choong, K., Krasnoff, J. B., Storer, T. W., Fielding, R. A., Bhasin, S. & Lebrasseur, N. K. 2010. Habitual physical activity levels are associated with performance in measures of physical function and mobility in older men. Journal of the American Geriatrics Society 58 (9), 1727-1733.

Nagi, S. Z. 1965. Some conceptual issues in disability and rehabilitation. In M. B. Sussman (Ed.) Sociology and Rehabilitation.Washington DC: American Sociological Association, 100-113.

NIH Consensus Panel 2004. NIH Consensus Statement on total knee replacement December 8-10, 2003. The Journal of Bone and Joint Surgery. American volume 86-A (6), 1328-1335.

Nilsdotter, A. K., Toksvig-Larsen, S. & Roos, E. M. 2009a. A 5 year prospective study of patient-relevant outcomes after total knee replacement. Osteoarthritis and Cartilage 17 (5), 601-606.

Nilsdotter, A. K., Toksvig-Larsen, S. & Roos, E. M. 2009b. Knee arthroplasty: are patients' expectations fulfilled? A prospective study of pain and function in 102 patients with 5-year follow-up. Acta Orthopaedica 80 (1), 55-61.

Noble, P. C., Gordon, M. J., Weiss, J. M., Reddix, R. N., Conditt, M. A. & Mathis, K. B. 2005. Does total knee replacement restore normal knee function? Clinical Orthopaedics and Related Research 431, 157-165.

Ohanian, H. C. 1989. Physics. (Second, Expanded edition) United States of America: W.W. Norton & Company, Inc.

Orbell, S., Espley, A., Johnston, M. & Rowley, D. 1998. Health benefits of joint replacement surgery for patients with osteoarthritis: Prospective evaluation using independent assessments in Scotland. Journal of Epidemiology and Community Health 52 (9), 564-570.

O'Reilly, S. & Doherty, M. 2003. Signs, symptoms and laboratory tests. In K. Brandt, M. Doherty & S. Lohmander (Eds.) Osteoarthritis. (Second edition) Oxford: Oxford University Press, 197-210.

O'Reilly, S., Jones, A. & Doherty, M. 1997. Muscle weakness in osteoarthritis. Current Opinion in Rheumatology 9 (3), 259-262.

O'Reilly, S. C., Jones, A., Muir, K. R. & Doherty, M. 1998. Quadriceps weakness in knee osteoarthritis: The effect on pain and disability. Annals of the Rheumatic Diseases 57 (10), 588-594.

Pantoja, P. D., Alberton, C. L., Pilla, C., Vendrusculo, A. P. & Kruel, L. F. 2009. Effect of resistive exercise on muscle damage in water and on land. Journal of Strength and Conditioning Research 23 (3), 1051-1054.

Parry-Billings, M., Newsholme, E. A. & Young, A. 1992. The uptake, storage, and release of metabolities by muscle. In J. G. Evans & T. F. Williams (Eds.) Oxford textbook of geriatric medicine. Oxford: University Press, 604-608.

Perhonen, M., Komi, P., Häkkinen, K., von Bonsdorff, H. & Partio, E. 1992. Strength training and neuromusular function in elderly people with total knee endoprosthesis. Scandinavian Journal of Medicine & Science in Sports 2, 234-243.

Perini, R., Milesi, S., Biancardi, L., Pendergast, D. R. & Veicsteinas, A. 1998. Heart rate variability in exercising humans: Effect of water immersion. European Journal of Applied Physiology and Occupational Physiology 77 (4), 326-332.

Petrella, J. K., Kim, J. S., Tuggle, S. C. & Bamman, M. M. 2007. Contributions of force and velocity to improved power with progressive resistance training in young and older adults. European Journal of Applied Physiology 99 (4), 343-351.

Petrick, M., Paulsen, T. & George, J. 2001. Comparison between quadriceps muscle strengthening on land and in water. Physiotherapy 87 (6), 310-317.

Petterson, S. C., Barrance, P., Buchanan, T., Binder-Macleod, S. & Snyder-Mackler, L. 2008. Mechanisms underlying quadriceps weakness in knee osteoarthritis. Medicine and Science in Sports and Exercise 40 (3), 422-427.

Petterson, S. C., Barrance, P., Marmon, A. R., Handling, T., Buchanan, T. S. & Snyder-Mackler, L. 2011. Time course of quadriceps strength, area, and activation after knee arthroplasty and strength training. Medicine and Science in Sports and Exercise 43 (2), 225-231.

Petterson, S. C., Mizner, R. L., Stevens, J. E., Raisis, L., Bodenstab, A., Newcomb, W. & Snyder-Mackler, L. 2009. Improved function from progressive strengthening interventions after total knee arthroplasty: A randomized clinical trial with an imbedded prospective cohort. Arthritis and Rheumatism 61 (2), 174-183.

Piva, S. R., Fitzgerald, G. K., Irrgang, J. J., Bouzubar, F. & Starz, T. W. 2004. Get up and go test in patients with knee osteoarthritis. Archives of Physical Medicine and Rehabilitation 85 (2), 284-289.

Portegijs, E., Sipilä, S., Alen, M., Kaprio, J., Koskenvuo, M., Tiainen, K. & Rantanen, T. 2005. Leg extension power asymmetry and mobility limitation in healthy older women. Archives of Physical Medicine and Rehabilitation 86 (9), 1838-1842.

Portegijs, E., Sipilä, S., Pajala, S., Lamb, S. E., Alen, M., Kaprio, J., Koskenvuo, M. & Rantanen, T. 2006. Asymmetrical lower extremity power deficit as a risk factor for injurious falls in healthy older women. Journal of the American Geriatrics Society 54 (3), 551-553.

Portegijs, E., Sipilä, S., Rantanen, T. & Lamb, S. E. 2008. Leg extension power deficit and mobility limitation in women recovering from hip fracture. American Journal of Physical Medicine & Rehabilitation 87 (5), 363-370.

Pöyhönen, T., Keskinen, K. L., Kyrölainen, H., Hautala, A., Savolainen, J. & Mälkiä, E. 2001a. Neuromuscular function during therapeutic knee exercise under water and on dry land. Archives of Physical Medicine and Rehabilitation 82 (10), 1446-1452.

Pöyhönen, T., Kyrölainen, H., Keskinen, K. L., Hautala, A., Savolainen, J. & Mälkiä, E. 2001b. Electromyographic and kinematic analysis of therapeutic knee exercises under water. Clinical Biomechanics (Bristol, Avon) 16 (6), 496-504.

Pöyhönen, T., Sipilä, S., Keskinen, K. L., 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 34 (12), 2103-2109.

Radin, E. L., Paul, I. L. & Rose, R. M. 1972. Role of mechanical factors in pathogenesis of primary osteoarthritis. Lancet 1 (7749), 519-522.

Rahmann, A. E., Brauer, S. G. & Nitz, J. C. 2009. A specific inpatient aquatic physiotherapy program improves strength after total hip or knee replacement surgery: A randomized controlled trial. Archives of Physical Medicine and Rehabilitation 90 (5), 745-755.

Rantanen, T. & Avela, J. 1997. Leg extension power and walking speed in very old people living independently. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 52 (4), M225-M231.

Rantanen, T., Guralnik, J. M., Ferrucci, L., Penninx, B. W., Leveille, S., Sipilä, S. & Fried, L. P. 2001. Coimpairments as predictors of severe walking disability in older women. Journal of the American Geriatrics Society 49 (1), 21-27.

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V. & Maganaris, C. N. 2009. Older adults employ alternative strategies to operate within their maximum capabilities when ascending stairs. Journal of Electromyography and Kinesiology 19 (2), e57-68.

Ritter, M. A., Carr, K. D., Keating, E. M. & Faris, P. M. 1994. Long-term outcomes of contralateral knees after unilateral total knee arthroplasty for osteoarthritis. The Journal of Arthroplasty 9 (4), 347-349.

Robertson, S., Frost, H., Doll, H. & O'Connor, J. J. 1998. Leg extensor power and quadriceps strength: An assessment of repeatability in patients with osteoarthritic knees. Clinical Rehabilitation 12 (2), 120-126.

Robinovitch, S. N., Hsiao, E. T., Sandler, R., Cortez, J., Liu, Q. & Paiement, G. D. 2000. Prevention of falls and fall-related fractures through biomechanics. Exercise and Sport Sciences Reviews 28 (2), 74-79.

Rodgers, J. A., Garvin, K. L., Walker, C. W., Morford, D., Urban, J. & Bedard, J. 1998. Preoperative physical therapy in primary total knee arthroplasty. The Journal of Arthroplasty 13 (4), 414-421.

Rossi, M. D., Brown, L. E. & Whitehurst, M. 2006. Knee extensor and flexor torque characteristics before and after unilateral total knee arthroplasty. American Journal of Physical Medicine & Rehabilitation 85 (9), 737-746.

Rossi, M. D. & Hasson, S. 2004. Lower-limb force production in individuals after unilateral total knee arthroplasty. Archives of Physical Medicine and Rehabilitation 85 (8), 1279-1284.

Russell, T. G., Buttrum, P., Wootton, R. & Jull, G. A. 2011. Internet-based outpatient telerehabilitation for patients following total knee arthroplasty: A randomized controlled trial. The Journal of Bone and Joint Surgery. American volume 93 (2), 113-120.

Sakari, R., Era, P., Rantanen, T., Leskinen, E., Laukkanen, P. & Heikkinen, E. 2010. Mobility performance and its sensory, psychomotor and musculoskeletal determinants from age 75 to age 80. Aging Clinical and Experimental Research 22 (1), 47-53.

Sakari-Rantala, R., Era, P., Rantanen, T. & Heikkinen, E. 1998. Associations of sensory-motor functions with poor mobility in 75- and 80-year-old people. Scandinavian Journal of Rehabilitation Medicine 30 (2), 121-127.

Sayers, S. P., Gibson, K. & Cook, C. R. 2012. Effect of high-speed power training on muscle performance, function, and pain in older adults with knee osteoarthritis: A pilot investigation. Arthritis Care & Research 64 (1), 46-53.

Schipplein, O. D. & Andriacchi, T. P. 1991. Interaction between active and passive knee stabilizers during level walking. Journal of Orthopaedic Research 9 (1), 113-119.

Schroer, W. C., Diesfeld, P. J., Reedy, M. E. & LeMarr, A. R. 2010. Isokinetic strength testing of minimally invasive total knee arthroplasty recovery. The Journal of Arthroplasty 25 (2), 274-279.

Segal, N. A. & Wallace, R. 2012. Tolerance of an aquatic power training program by older adults with symptomatic knee osteoarthritis. Arthritis 2012:895495. Epub 2012 Sep 13.

Shumway-Cook, A. & Woollacott, M. H. 2007. Motor Control: Translating Research into Clinical Practice. (Fourth edition) USA: Lippincott Williams & Wilkins.

Silva, L. E., Valim, V., Pessanha, A. P., Oliveira, L. M., Myamoto, S., Jones, A. & Natour, J. 2008. Hydrotherapy versus conventional land-based exercise for the management of patients with osteoarthritis of the knee: A randomized clinical trial. Physical Therapy 88 (1), 12-21.

Silva, M., Shepherd, E. F., Jackson, W. O., Pratt, J. A., McClung, C. D. & Schmalzried, T. P. 2003. Knee strength after total knee arthroplasty. The Journal of Arthroplasty 18 (5), 605-611.

Simic, M., Bennell, K. L., Hunt, M. A., Wrigley, T. V. & Hinman, R. S. 2011. Contralateral cane use and knee joint load in people with medial knee osteoarthritis: The effect of varying body weight support. Osteoarthritis and Cartilage 19 (11), 1330-1337.

Sipilä, S., Elorinne, M., Alen, M., Suominen, H. & Kovanen, V. 1997. Effects of strength and endurance training on muscle fibre characteristics in elderly women. Clinical Physiology (Oxford, England) 17 (5), 459-474.

Sipilä, S., Multanen, J., Kallinen, M., Era, P. & Suominen, H. 1996. Effects of strength and endurance training on isometric muscle strength and walking speed in elderly women. Acta Physiologica Scandinavica 156 (4), 457-464.

Sipilä, S. & Suominen, H. 1995. Effects of strength and endurance training on thigh and leg muscle mass and composition in elderly women. Journal of Applied Physiology 78 (1), 334-340.

Snyder, A. R., Parsons, J. T., Valovich McLeod, T. C., Curtis Bay, R., Michener, L. A. & Sauers, E. L. 2008. Using disablement models and clinical outcomes assessment to enable evidence-based athletic training practice, part I: Disablement models. Journal of Athletic Training 43 (4), 428-436.

Stevens-Lapsley, J. E., Balter, J. E., Wolfe, P., Eckhoff, D. G. & Kohrt, W. M. 2012. Early neuromuscular electrical stimulation to improve quadriceps muscle strength after total knee arthroplasty: A randomized controlled trial. Physical Therapy 92 (2), 210-226.

Suetta, C., Aagaard, P., Magnusson, S. P., Andersen, L. L., Sipilä, S., Rosted, A., Jakobsen, A. K., Duus, B. & Kjaer, M. 2007. Muscle size, neuromuscular activation, and rapid force characteristics in elderly men and women: Effects of unilateral long-term disuse due to hip-osteoarthritis. Journal of Applied Physiology 102 (3), 942-948.

Taaffe, D. R., Henwood, T. R., Nalls, M. A., Walker, D. G., Lang, T. F. & Harris, T. B. 2009. Alterations in muscle attenuation following detraining and retraining in resistance-trained older adults. Gerontology 55 (2), 217-223.

Takeshima, N., Rogers, M. E., Watanabe, E., Brechue, W. F., Okada, A., Yamada, T., Islam, M. M. & Hayano, J. 2002. Water-based exercise improves health-related aspects of fitness in older women. Medicine and Science in Sports and Exercise 34 (3), 544-551.

Taunton, J. E., Rhodes, E. C., Wolski, L. A., Donelly, M., Warren, J., Elliot, J., McFarlane, L., Leslie, J., Mitchell, J. & Lauridsen, B. 1996. Effect of land-based and water-based fitness programs on the cardiovascular fitness, strength and flexibility of women aged 65-75 years. Gerontology 42 (4), 204-210.

Thein, J. M. & Brody, L. T. 2000. Aquatic-based rehabilitation and training for the shoulder. Journal of Athletic Training 35 (3), 382-389.

Thelen, D. G., Muriuki, M., James, J., Schultz, A. B., Ashton-Miller, J. A. & Alexander, N. B. 2000. Muscle activities used by young and old adults when stepping to regain balance during a forward fall. Journal of Electromyography and Kinesiology 10 (2), 93-101.

Thelen, D. G., Schultz, A. B., Alexander, N. B. & Ashton-Miller, J. A. 1996. Effects of age on rapid ankle torque development. The Journals of

Gerontology. Series A, Biological Sciences and Medical Sciences 51 (5), M226-M232.

Thomas, S. G., Pagura, S. M. & Kennedy, D. 2003. Physical activity and its relationship to physical performance in patients with end stage knee osteoarthritis. The Journal of Orthopaedic and Sports Physical Therapy 33 (12), 745-754.

Tidhar, D., Drouin, J. & Shimony, A. 2007. Aqua lymphatic therapy in managing lower extremity lymphedema. The Journal of Supportive Oncology 5 (4), 179-183.

Tiedemann, A., Sherrington, C. & Lord, S. R. 2005. Physiological and psychological predictors of walking speed in older community-dwelling people. Gerontology 51 (6), 390-395.

Tiedemann, A. C., Sherrington, C. & Lord, S. R. 2007. Physical and psychological factors associated with stair negotiation performance in older people. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 62 (11), 1259-1265.

Tomas-Carus, P., Hakkinen, A., Gusi, N., Leal, A., Hakkinen, K. & Ortega-Alonso, A. 2007. Aquatic training and detraining on fitness and quality of life in fibromyalgia. Medicine and Science in Sports and Exercise 39 (7), 1044-1050.

Tracey, K. J. 2007. Physiology and immunology of the cholinergic antiinflammatory pathway. The Journal of Clinical Investigation 117 (2), 289-296.

Triplett, N. T., Colado, J. C., Benavent, J., Alakhdar, Y., Madera, J., Gonzalez, L. M. & Tella, V. 2009. Concentric and impact forces of single-leg jumps in an aquatic environment versus on land. Medicine and Science in Sports and Exercise 41 (9), 1790-1796.

Tsourlou, T., Benik, A., Dipla, K., Zafeiridis, A. & Kellis, S. 2006. The effects of a twenty-four-week aquatic training program on muscular strength performance in healthy elderly women. Journal of Strength and Conditioning Research 20 (4), 811-818.

United States National Library of Medicine 2011. Medical Subject Headings (MeSH).

van Dijk, G. M., Veenhof, C., Lankhorst, G. J. & Dekker, J. 2009. Limitations in activities in patients with osteoarthritis of the hip or knee: The relationship with body functions, comorbidity and cognitive functioning. Disability and Rehabilitation 31 (20), 1685-1691.

Verbrugge, L. M. & Jette, A. M. 1994. The disablement process. Social Science & Medicine 38 (1), 1-14.

Visser, M., Goodpaster, B. H., Kritchevsky, S. B., Newman, A. B., Nevitt, M., Rubin, S. M., Simonsick, E. M. & Harris, T. B. 2005. Muscle mass, muscle strength, and muscle fat infiltration as predictors of incident mobility limitations in well-functioning older persons. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 60 (3), 324-333.

Walsh, M., Woodhouse, L. J., Thomas, S. G. & Finch, E. 1998. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. Physical Therapy 78 (3), 248-258.

Wang, T. J., Belza, B., Elaine Thompson, F., Whitney, J. D. & Bennett, K. 2007. Effects of aquatic exercise on flexibility, strength and aerobic fitness in adults with osteoarthritis of the hip or knee. Journal of Advanced Nursing 57 (2), 141-152.

Wang, T. J., Lee, S. C., Liang, S. Y., Tung, H. H., Wu, S. F. & Lin, Y. P. 2011. Comparing the efficacy of aquatic exercises and land-based exercises for patients with knee osteoarthritis. Journal of Clinical Nursing 20 (17-18), 2609-2622.

West, C. G., Gildengorin, G., Haegerstrom-Portnoy, G., Schneck, M. E., Lott, L. & Brabyn, J. A. 2002. Is vision function related to physical functional ability in older adults? Journal of the American Geriatrics Society 50 (1), 136-145.

World Health Organization 2004. Toimintakyvyn, toimitarajoitteiden ja terveyden kansainvälinen luokitus ICF. Helsinki: Stakes.

World Health Organization 2001. International classification of functioning, disability and health: ICF. Geneva: World Health Organization.

Wyatt, F. B., Milam, S., Manske, R. C. & Deere, R. 2001. The effects of aquatic and traditional exercise programs on persons with knee osteoarthritis. Journal of Strength and Conditioning Research 15 (3), 337-340.

Wylde, V., Dieppe, P., Hewlett, S. & Learmonth, I. D. 2007. Total knee replacement: Is it really an effective procedure for all? The Knee 14 (6), 417-423.

Yoshida, Y., Mizner, R. L., Ramsey, D. K. & Snyder-Mackler, L. 2008. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. Clinical Biomechanics (Bristol, Avon) 23 (3), 320-328.

Zhang, W., Nuki, G., Moskowitz, R. W., Abramson, S., Altman, R. D., Arden, N. K., Bierma-Zeinstra, S., Brandt, K. D., Croft, P., Doherty, M., Dougados, M., Hochberg, M., Hunter, D. J., Kwoh, K., Lohmander, L. S. & Tugwell, P. 2010. OARSI recommendations for the management of hip and knee osteoarthritis: part III: Changes in evidence following systematic cumulative update of research published through January 2009. Osteoarthritis and Cartilage 18 (4), 476-499.

ORIGINAL PAPERS

I

ASYMMETRICAL KNEE EXTENSOR POWER DEFICIT SLOWS STAIR ASCENSION IN PATIENTS WITH END-STAGE KNEE OSTEOARTHRITIS: A CROSS-SECTIONAL STUDY

by

Valtonen A, Pöyhönen T, Manninen M, Heinonen A, Sipilä S.

Submitted for publication

II

MUSCLE DEFICITS PERSIST AFTER UNILATERAL KNEE REPLACEMENT AND HAVE IMPLICATIONS FOR REHABILITATION

by

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Muscle Deficits Persist After Unilateral Knee Replacement and Have Implications for Rehabilitation

Anu Valtonen, Tapani Pöyhönen, Ari Heinonen, Sarianna Sipilä

A. Valtonen, PT, MSc, is Researcher, Rehabilitation and Pain Unit, Kymenlaakso Central Hospital, Kotkantie 41, FIN-48210 Kotka, Finland, and Department of Health Sciences, University of Jyväskylä, Jyväskylä, Finland. Address all correspondence to Ms Valtonen at: anu.m.valtonen@jyu.fi.

T. Pöyhönen, PT, PhD, is Exercise Physiologist, Rehabilitation and Pain Unit, Kymenlaakso Central Hospital.

A. Heinonen, PT, PhD, is Professor, Department of Health Sciences, University of Jyväskylä.

S. Sipilä, PT, PhD, is Research Director, Finnish Centre for Interdisciplinary Gerontology, Department of Health Sciences, University of Jyväskylä.

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Background. Knee joint arthritis causes pain, decreased range of motion, and mobility limitation. Knee replacement reduces pain effectively. However, people with knee replacement have decreases in muscle strength ("force-generating capacity") of the involved leg and difficulties with walking and other physical activities.

Objective and Design. The aim of this cross-sectional study was to determine the extent of deficits in knee extensor and flexor muscle torque and power (ability to perform work over time) and in the extensor muscle cross-sectional area (CSA) after knee joint replacement. In addition, the association of lower-leg muscle deficits with mobility limitations was investigated.

Methods. Participants were 29 women and 19 men who were 55 to 75 years old and had undergone unilateral knee replacement surgery an average of 10 months earlier. The maximal torque and power of the knee extensor and flexor muscles were measured with an isokinetic dynamometer. The knee extensor muscle CSA was measured with computed tomography. The symmetry deficit between the knee that underwent replacement surgery ("operated knee") and the knee that did not undergo replacement surgery ("nonoperated knee") was calculated. Maximal walking speed and stair-ascending and stair-descending times were assessed.

Results. The mean deficits in knee extensor and flexor muscle torque and power were between 13% and 27%, and the mean deficit in the extensor muscle CSA was 14%. A larger deficit in knee extension power predicted slower stair-ascending and stair-descending times. This relationship remained unchanged when the power of the nonoperated side and the potential confounding factors were taken into account.

Limitations. The study sample consisted of people who were relatively healthy and mobile. Some participants had osteoarthritis in the nonoperated knee.

Conclusions. Deficits in muscle torque and power and in the extensor muscle CSA were present 10 months after knee replacement, potentially causing limitations in negotiating stairs. To prevent mobility limitations and disability, deficits in lower-limb power should be considered during rehabilitation after knee replacement.

With an aging population, the prevalence of degenerative joint diseases, such as knee joint arthritis, increases and thus adds to the burden of health care systems in Western societies. Knee joint arthritis causes pain, decreased range of motion, and mobility limitations. Knee joint replacement is a common surgical procedure that effectively reduces pain.[1–4] However, several studies[2,5–12] have shown that people with knee replacement surgery have difficulties with walking and other physical activities. Mobility undergoes an expected decline during the first month after knee replacement.[7] Mizner et al[7] reported that performance in stair-climbing and "stand-up-and-go" tests returned to the preoperative level at 2 months after surgery. Therefore, although functional ability may improve to the preoperative level, which already is severely impaired because of pain and long-term disuse, it rarely reaches the level in age-matched control subjects.[5,12,13] For example, Walsh et al[5] and Yoshida et al[12] reported that people with knee replacement had a lower maximal walking speed[5,12] and negotiated stairs more slowly[5] than control subjects even beyond 1 year after surgery.

Mobility limitations are known to be associated with decreases in muscle strength (force-generating capacity) and power (ability to perform work over time). These impairments continue to persist for several months after surgery.[5,7,8,10,14–16] Several investigators[7,11,14,17–19] have reported declines of 21% to 42% in knee extensor torque and power for the knee that underwent replacement surgery ("operated knee") compared with the knee that did not undergo replacement surgery ("nonoperated knee") at 3 to 6 months after surgery. Furthermore, even at 1 to 2 years after knee replacement surgery, a difference of 12% to 29% between the knee extensor muscles has been reported.[5,9,17] Similar deficits have been reported for knee flexor muscle strength.[5,14] Knee extensor muscle strength has been reported to remain 19% to 35% lower in people with knee replacement than in age-matched people, even at 13 years after surgery.[5,11,20–22]

Previous studies[11,18,23,24] indicated that there is a decline in the knee extensor muscle cross-sectional area (CSA) of the operated leg during the early recovery phase—1 to 3 months after surgery—compared with the preoperative CSA. To our knowledge, no studies comparing muscle CSA between the legs or reporting spontaneous long-term recovery of muscle CSA after knee replacement surgery have been done.

Mobility limitations may be related to lower-limb muscle deficits, that is, side-to-side differences between the operated leg and the nonoperated leg. Previous studies showed that in people who are healthy[25,26] and in some clinical populations,[27–29] lower-limb power deficits have detrimental effects on mobility. Portegijs et al[25] reported that in people who were healthy, knee extensor power asymmetry was associated with a lower walking speed. Additionally, they found that in women recovering from hip fractures, a larger power deficit was associated with limitations in stair-climbing ability.[29]

To date, little is known about muscle deficits and their persistent effects on mobility limitations in people with knee replacement. Therefore, the purpose of this study was to determine the extent of muscle deficits in knee extensor and flexor muscle torque and power and in the extensor muscle CSA and composition in a group of people who had undergone unilateral knee replacement an average of 10 months earlier. In addition, the association of lower-limb muscle deficits with mobility limitations was investigated.

Methods

Setting and Participants

A total of 201 people who, according to the physical therapy records of Kymenlaakso Central Hospital, had undergone unilateral knee replacement 4 to 18 months before the study were informed about the study. Eighty-six people contacted the research personnel. People with bilateral knee arthroplasty, revision arthroplasty, hemiarthroplasty, severe cardiovascular diseases, dementia, rheumatoid arthritis, or major surgery on either of the knees were excluded from the study. Thus, 48 eligible volunteers (29 women and 19 men; age range=55–75 years) participated in the study.

The physical characteristics of the participants are shown in Table 1. All of the participants had undergone knee replacement surgery with cement fixation. Eight of the 48 participants had osteoarthritis diagnosed in the nonoperated knee.

The data used in this cross-sectional study were collected in 2 phases. Because of the small number of eligible subjects in spring 2005, the data collection was repeated in autumn 2005 with the same recruitment protocol, infrastructure, and staff. Before the laboratory examinations, the participants were informed about the study and gave written informed consent.

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Table 1.
Physical Characteristics of Participants

Characteristic	Women (n=29)			Men (n=19)		
	X̅	SD	Range	X̅	SD	Range
Age (y)	67.7	5.5	57–75	65.2	6.2	55–75
Body weight (kg)	79.4	13.6	56.0–115.2	89.1	15.9	70.1–122.0
Body height (cm)	163.3	5.4	152–172	175.4	7.2	161–189
Body mass index	29.7	4.6	21.9–42.2	28.8	3.7	23.2–34.5
Time after surgery (mo)	9.2	4.5	5–18	9.8	4.2	4–18
Walking speed (m/s)	1.7	0.3	0.9–2.3	2.1	0.6	0.9–3.8
Stair-ascending time (s)	5.9	2.5	3.6–13.2	3.9	1.8	2.3–10.3
Stair-descending time (s)	6.7	4.2	3.1–21.8	4.1	2.2	2.3–11.2

Measurements

The clinical history of the participants, including their medications and diseases, were confirmed by a physician before the laboratory examinations. Body height and body weight were measured by use of standard procedures. The day-to-day intrarater reproducibility of the measurements (muscle torque, power, walking speed, stair ascending, and stair descending) was measured in our laboratory with a pilot sample. The measurements were performed twice by use of identical procedures, with an interval of 1 week between the measurement occasions.

In a pilot study (unpublished), 17 volunteers (12 women and 5 men; mean age=77 years, range=55–75) with unilateral knee replacement an average of 8 months (range=4–12) after surgery participated in the measurements. The intraclass correlation coefficient (ICC) was calculated by use of a 1-way random model. The participants in the pilot sample were not included in the sample in the current study. The reliability (ICC) of each measurement is presented in context with the measurement.

Muscle torque and power. The maximal isokinetic torque (N·m) of the knee extensor and flexor muscles was measured by use of an isokinetic dynamometer* with a sampling frequency of 100 Hz and a measurement error of 1% through the entire range of motion. The dynamometer was calibrated before each measurement session according to the standard procedure recommended by the manufacturer. Before the measurement session, the participants were carefully familiarized with the testing procedure.

For each leg, the axis of rotation of the dynamometer was aligned with the condylus lateralis femoris. The lever arm of the dynamometer was attached around the ankle 2.5 cm above the midpoint of the malleolus lateralis. The hip and thigh were stabilized with straps. The full knee range of motion was measured. The nonoperated leg was measured first. After a few submaximal flexion-extension movements, 3 maximal continuous flexion-extension trials were performed at an angular velocity of 60°/s, and 5 trials were performed at a velocity of 180°/s, with 2 to 3 minutes of rest between trials. The participants were verbally encouraged to make a maximal effort throughout the whole range of motion. The highest peak torque (N·m) at an angular velocity of 60°/s was analyzed. Peak power was analyzed in extension and flexion at an angular velocity of 180°/s. The ICC of the isokinetic parameters for the operated knee in the people with knee replacement varied between .90 and .97.

Muscle CSA and attenuation. Computed tomography (CT) scans were obtained from both midthighs by use of a Siemens Somatom DR Scanner† with the subject in a supine position. The midthigh was defined as the midpoint between the greater trochanter and the lower edge of the patella. The scans were analyzed by use of software developed for cross-sectional CT image analysis (Geanie 2.1‡), which separates fat and lean tissues on the basis of radiological density (measured as attenuation in Hounsfield units) limits. The quadriceps femoris muscle was determined manually by drawing a line along the fascial plane. A lower mean attenuation value reflects greater fat infiltration within the muscle. The Figure shows an example of the CT analysis. The CT measurements and analyses were conducted in a masked fashion. In our previous study,[30] the coefficients of variation between 2 consecutive repeated measurements were calculated and shown to be less than 1% for lean tissue Hounsfield units and 1% to 2% for the CSA.

* Biodex Medical Systems Inc, 20 Ramsey Rd, Shirley, NY 11967-4704.

† Siemens AG, Erlangen, Germany.
‡ Commit Ltd, Espoo, Finland.

Mobility Assessment

Walking speed. Maximal walking speed over 10 m was measured in the hospital corridor. Walking time was recorded by use of photocells.[§] Participants were instructed to walk as fast as possible without compromising their safety. All participants wore thin aquatic shoes and were allowed 3 m for acceleration. Each participant performed 2 trials, separated by a 1-minute rest period, and the fastest time was accepted as the best result. The ICC for maximal walking speed in people with knee replacement was .86.

Negotiating stairs. Times to ascend and descend a 10-step staircase were measured in the hospital corridor. The stair height was 17 cm, and the depth was 29.5 cm. The participants were instructed to step alternately on each stair and walk as fast as possible without compromising their safety. The use of a handrail or taking a step on each stair with both feet was allowed only when necessary. Three participants stepped on each stair with both feet in the stair-ascending task, and 7 did so in the stair-descending task. Ascending and descending times were recorded by use of photocells.[§] Each participant performed 2 ascending trials, followed by a 1-minute rest period, and then performed 2 descending trials. The fastest times were accepted as the best results. The ICCs were .90 for stair ascending and .73 for stair descending in the participants with knee replacement.

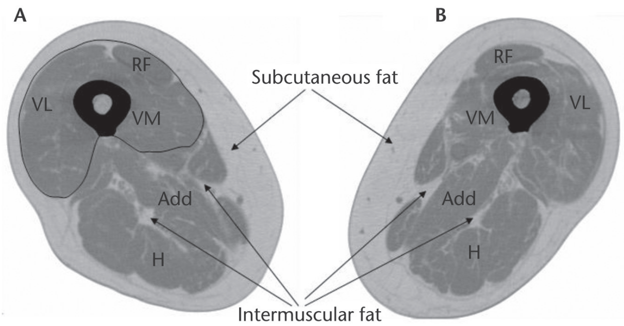

Figure.
Cross-sectional computed tomography scans obtained from the midthighs of a 70-year-old woman who had undergone total unilateral knee replacement 9 months earlier. (A) Thigh on side opposite surgery; total muscle cross-sectional area was 79 cm², mean attenuation of the muscle tissue was 39.1 Hounsfield units, and total fat cross-sectional area was 60.8 cm². (B) Thigh on side of surgery; total muscle cross-sectional area was 68 cm², mean attenuation of the muscle tissue was 35.8 Hounsfield units, and total fat cross-sectional area was 68.1 cm². Muscles: Add=adductor, H=hamstring, RF=rectus femoris, VL=vastus lateralis, VM=vastus medialis.

Data Analysis

The differences in muscle characteristics (torque, power, CSA, and attenuation) between the operated leg and the nonoperated leg were analyzed with a paired 2-tailed Student *t* test. The muscle symmetry deficit (relative difference) was calculated according to the following equation: symmetry deficit (%) = [(value for nonoperated leg − value for operated leg)/value for nonoperated leg] × 100. Stepwise multiple linear regression models were used to examine the most relevant muscle deficit (muscle torque, power, CSA, and attenuation) and muscle power variable associated with mobility limitations. Variables with nonsignificant independent associations with mobility were removed from the final model. Thus, the final model contained only the explanatory variables that had significant independent associations with mobility limitations and that had the highest possible proportion of the variance explained by coefficients of determination (adjusted R^2). The models were further adjusted for age, sex, and time after surgery. For the regression analysis, the results obtained for men and women were pooled because there were no sex differences in age, time after surgery, or any of the muscle deficit variables. Significance was set at $P<.05$. Statistical analyses were run with SPSS (version 13.0) software.[‖]

Results

Knee Extensor Muscles

For the entire group, the mean knee extensor torque, power, CSA, and attenuation values for the operated side were significantly ($P<.001$) lower than those for the nonoperated side. For the knee extensor muscles, more than 97% of the participants had lower or equal values in the operated leg than in the nonoperated leg. The mean knee extension torque deficit was 27% (95% confidence interval [CI]=22%–32%), and the mean knee extension power deficit was 23% (95% CI=17%–29%). The mean knee extensor muscle CSA deficit was 14% (95% CI=11%–18%), and the mean knee extensor attenuation deficit was 9% (95% CI=6%–11%). The results for the knee extensor muscles are shown in Table 2.

§ Newtest Oy, Koulukatu 31 B 11, FIN-90100, Oulu, Finland.

‖ SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

Table 2.
Knee Extensor Torque, Power, Cross-Sectional Area, and Attenuation in Operated and Nonoperated Knees[a]

Group	Measure	Operated Knee		Nonoperated Knee		P^b	Symmetry Deficit, %[c] (95% CI)
		$\bar{X}$	SD	$\bar{X}$	SD		
Women	Torque, N·m	64.7	17.2	89.9	20.5	<.001	26 (18–34)
	Power, W	95.4	35.1	127.9	31.8	<.001	26 (18–34)
	CSA, cm²	36.6	8.5	42.4	8.2	<.001	14 (8–19)
	Attenuation, HU	36.8	5.0	40.3	3.8	<.001	9 (5–13)
Men	Torque, N·m	100.0	27.0	141.5	35.5	<.001	29 (22–36)
	Power, W	148.5	44.9	190.1	60.9	.001	19 (9–28)
	CSA, cm²	52.7	12.0	62.5	10.9	<.001	16 (11–21)
	Attenuation, HU	39.2	6.4	42.8	5.2	<.001	9 (5–13)
All	Torque, N·m	79.6	27.9	111.7	37.7	<.001	27 (22–32)
	Power, W	117.3	47.1	153.6	55.0	<.001	23 (17–29)
	CSA, cm²	42.9	12.7	50.3	13.6	<.001	14 (11–18)
	Attenuation, HU	37.7	5.6	41.3	4.5	<.001	9 (6–11)

[a] CI=confidence interval, CSA=cross-sectional area, HU=Hounsfield units.
[b] Determined with the equality of means test for the operated knee versus the nonoperated knee.
[c] Symmetry deficit (%)=[(value for nonoperated leg − value for operated leg)/value for nonoperated leg] × 100.

Knee Flexor Muscles

For the entire group, the mean knee flexor torque and power values for the operated side were significantly ($P<.001$) lower than those for the nonoperated side. For the knee flexor muscles, over 87% of the participants had lower or equal values in the operated leg than in the nonoperated leg. The mean knee flexion torque deficit was 13% (95% CI=7%–19%), and the mean knee flexion power deficit was 19% (95% CI=11%–27%). The results for the knee flexor muscles are shown in Table 3.

Mobility

For the entire group, the mean (SD) maximal 10-m walking speed, stair-ascending time, and stair-descending time were 1.9 (0.5) m/s, 5.1 (2.4) seconds, and 5.6 (3.7) seconds, respectively. The results for mobility are shown separately for women and men in Table 1.

Multivariate regression analysis was performed to examine the association among muscle deficit, muscle power production, and negotiating stairs (Tabs. 4 and 5). A larger knee extension power deficit, together with low knee flexion power on the nonoperated side, predicted slower stair-ascending time (Tab. 4). Adjustments for age, sex, and time after surgery did not materially change the association. In addition, a larger knee extension power deficit, together

Table 3.
Knee Flexor Torque and Power in Operated and Nonoperated Knees[a]

Group	Measure	Operated Knee		Nonoperated Knee		P^b	Symmetry Deficit, %[c] (95% CI)
		$\bar{X}$	SD	$\bar{X}$	SD		
Women	Torque, N·m	40.9	12.1	48.9	11.2	.001	16 (7–24)
	Power, W	85.1	32.5	109.8	31.3	<.001	22 (13–32)
Men	Torque, N·m	71.4	17.9	80.4	21.2	.016	10 (1–18)
	Power, W	133.4	43.5	168.1	54.3	.012	14 (0–28)
All	Torque, N·m	53.8	21.2	62.2	22.4	<.001	13 (7–19)
	Power, W	105.0	44.1	133.9	50.9	<.001	19 (11–27)

[a] CI=confidence interval.
[b] Determined with the equality of means test for the operated knee versus the nonoperated knee.
[c] Symmetry deficit (%)=[(value for nonoperated leg − value for operated leg)/value for nonoperated leg] × 100.

Table 4.
Factors Explaining Variability in Stair-Ascending Time in People With Unilateral Knee Replacement

Factor	Crude[a]			Adjusted[b]		
	B (SEE)	β	P	B (SEE)	β	P
Extension power deficit	0.042 (0.013)	.404	.002	0.039 (0.014)	.379	.006
Flexion power of the nonoperated knee, W	−0.020 (0.005)	−.481	<.001	−0.017 (0.007)	−.423	.021
Age, y				0.007 (0.052)	.021	.888
Sex				−0.333 (0.663)	−.080	.618
Time after surgery, mo				−0.021 (0.060)	−.044	.732

[a] R^2=.372 for the crude model. B=unstandardized regression coefficient, SEE=standard error of the estimate.
[b] R^2=.378 for the adjusted model.

with low knee flexion power on the nonoperated side, predicted slower stair-descending time (Tab. 5). Adjustments for potential confounding factors did not materially change the association.

Discussion

The results of this study showed that at an average of 10 months after knee replacement surgery, the operated leg was significantly weaker than the nonoperated leg, and the extensor muscle CSA in the operated leg was smaller than that in the nonoperated leg. A larger knee extension power deficit predicted slower stair-ascending and stair-descending times. This relationship remained unchanged when the power of the nonoperated side and potential confounding factors were taken into account. Lower-limb muscle power, especially the difference between the legs, seemed to be critical for mobility limitations; therefore, it should be considered during evaluations of mobility in both people who are healthy and people who have disabilities.

In the majority of the participants, the operated leg was weaker than the nonoperated leg, and the muscle CSA of the operated leg was smaller than that of the nonoperated leg. The results of the present study are in line with those of previous studies that investigated muscle force 6 to 12 months after unilateral knee replacement.[5,7,14,17] A comparison of the results of the present study and those previously reported is difficult because we calculated the muscle strength deficit for each participant individually, whereas in earlier studies, side-to-side differences were estimated from group mean values. Overall, the deficit in the knee extensor muscles after knee replacement surgery is considerable and can also be prolonged; the leg with the knee replacement has been shown to be significantly weaker than the legs of healthy control subjects for as long as 13 years after the surgery.[5,20–22] Previous studies[7,14,17] showed a difference of 15% to 29% in knee extension torque between the operated leg and the nonoperated leg, which is in line with the 27% difference found in the present study. Rossi and Hasson,[16] however, reported a marked, 38% difference in the findings for a single leg press between the operated leg and the nonoperated leg at 16 months after knee replacement. This large side-to-side difference may have been attributable to the multiple muscle groups involved in the leg press.

We also found a marked knee flexor torque deficit (ie, 13%) after an average of 10 months from knee replace-

Table 5.
Factors Explaining Variability in Stair-Descending Time in People With Unilateral Knee Replacement

Factor	Crude[a]			Adjusted[b]		
	B (SEE)	β	P	B (SEE)	β	P
Extension power deficit	0.060 (0.018)	.421	.001	0.061 (0.019)	.425	.003
Flexion power of the nonoperated knee, W	−0.026 (0.007)	−.455	.001	−0.021 (0.010)	−.369	.043
Age, y				0.063 (0.071)	.129	.383
Sex				−0.218 (0.917)	−.038	.813
Time after surgery, mo				0.021 (0.083)	.032	.800

[a] R^2=.362 for the crude model. B=unstandardized regression coefficient, SEE=standard error of the estimate.
[b] R^2=.376 for the adjusted model.

ment. This finding supports the results of 2 earlier studies reporting a side-to-side difference of 16% to 23% in knee flexor muscles at 6 to 12 months after surgery.[5,14] Therefore, this muscle group should receive attention during assessment and rehabilitation of degenerative knee joint problems.

We also found 19% to 23% deficits in knee extensor and flexor muscle power; these values were somewhat higher than the value reported by Lamb and Frost,[6] who found a difference of 18% in leg extension power at 6 months after knee replacement. This substantial deficit should be taken into consideration in rehabilitation programs because in daily activities it is important to have the muscle power needed to produce effective force quickly to generate desirable or prevent undesirable movements. In particular, the ability to recover from a stumble is highly dependent on the power and coordination of the leg muscles.[31–33] In addition, Portegijs et al[26] found that, even in people who were healthy, a knee extension power deficit was associated with falls. Although we did not evaluate falls after knee replacement in the present study, we would argue in accordance with the literature[26,28] that a power deficit should be taken seriously as a risk factor for falls and therefore should be considered in knee replacement rehabilitation.

The extensor muscle CSA deficit was marked (14%) in the present study. To our knowledge, a long-term muscle CSA deficit has not been studied. Previous studies[11,18,23,24] showed declines of 5% to 20% (relative to preoperative values) in knee extensor muscle CSA in the operated leg at 1 to 3 months after knee replacement. In the present study, the most likely reason for the large side-to-side difference, in addition to long-term pain and disuse because of osteoarthritis, was the surgery itself, which resulted in a long wound, considerable surgical trauma, and a long recovery time. In people with hip osteoarthritis after prolonged unilateral disuse, the preoperative side-to-side difference in quadriceps muscle CSA between the affected leg and the nonaffected leg has been reported to be smaller (8%–10%).[34] Loss of muscle CSA (atrophy) is an important mechanism underlying muscle weakness, although the amount of muscle CSA lost is often smaller than the amount of muscle force lost.[35] A muscle CSA deficit of 14% may present a challenge for rehabilitation because even in older subjects who were healthy, a progressive strength training regimen lasting 3 to 4 months was shown to have an effect of less than 10% on muscle CSA.[30,36]

Decreased lower-limb muscle power is one of the factors underlying mobility limitations in older adults.[37–39] Mizner et al[7] and Mizner and Snyder-Mackler[8] reported that weakness of the knee extensor muscles in people with a total knee replacement was closely associated with mobility limitations, especially in stair-climbing tasks and the Timed "Up & Go" Test. According to Lamb and Frost,[6] leg extension power is an important determinant of walking speed and stair-ascending time after knee replacement. Portegijs et al[25] reported that extension power asymmetry was also associated with a lower walking speed in older women who were healthy. In the present study, large power and torque deficits were associated with slow stair-ascending and stair-descending times but not with maximal walking speed. This result is in line with the results of Portegijs et al,[29] who found that in women recovering from hip fracture, a large power deficit was associated with limitations in stair climbing but not with walking speed. It would appear that because walking is a common functional task, the nonoperated leg may be able to compensate for problems with the operated leg. However, to perform more-demanding functional tasks, such as stair ascending and stair descending, a person needs more power and force production in the knee extensor muscles.[7,8]

The present study had some limitations. The study was a cross-sectional analysis without follow-up; therefore, we cannot speculate on the causal relationships or the associations over time. The study population consisted of people who were relatively healthy and mobile and had undergone successful unilateral knee replacement procedures. It is impossible to know whether people with more-extensive mobility problems might have dropped out; such a situation might have reduced the variance in muscle deficits and in mobility problems. In addition, some of the participants had osteoarthritis in the nonoperated knee, and this condition may have influenced the muscle deficits in the lower legs. The clear strength of the present study is the large number of measurements of deficits in muscle torque, power, and CSA. The results of this cross-sectional study need to be confirmed in future prospective and experimental studies.

Conclusion

Deficits in muscle power or torque are clinically important during evaluations of mobility limitations up to nearly 1 year after surgery. Because the major goals in the rehabilitation of musculoskeletal problems are to restore a person's mobility and functional capacity and to prevent mobility disability, increasing muscle power, especially in the operated leg, may be one of the central issues to address during the rehabilitation process. The findings of this study are potentially useful for planning preventive and rehabilitative strategies; however, further work is needed.

All authors provided concept/idea/research design, writing, and data collection and analysis. Dr Pöyhönen and Dr Heinonen provided project management. Ms Valtonen, Dr Pöyhönen, and Dr Heinonen provided fund procurement. Ms Valtonen and Dr Pöyhönen provided participants. Dr Pöyhönen provided facilities/equipment. Dr Heinonen provided consultation (including review of manuscript before submission).

The study was approved by the ethics committee of Kymenlaakso Central Hospital.

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References

1 Martin SD, Scott RD, Thornhill TS. Current concepts of total knee arthroplasty. *J Orthop Sports Phys Ther*. 1998;28:252–261.

2 Orbell S, Espley A, Johnston M, Rowley D. Health benefits of joint replacement surgery for patients with osteoarthritis: prospective evaluation using independent assessments in Scotland. *J Epidemiol Community Health*. 1998;52:564–570.

3 NIH Consensus Panel. NIH Consensus Statement on total knee replacement December 8–10, 2003. *J Bone Joint Surg Am*. 2004;86:1328–1335.

4 Jones DL, Westby MD, Greidanus N, et al. Update on hip and knee arthroplasty: current state of evidence. *Arthritis Rheum*. 2005;53:772–780.

5 Walsh M, Woodhouse LJ, Thomas SG, Finch E. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. *Phys Ther*. 1998;78:248–258.

6 Lamb SE, Frost H. Recovery of mobility after knee arthroplasty: expected rates and influencing factors. *J Arthroplasty*. 2003;18:575–582.

7 Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. *J Orthop Sports Phys Ther*. 2005;35:424–436.

8 Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *J Orthop Res*. 2005;23:1083–1090.

9 Rossi MD, Brown LE, Whitehurst M. Knee extensor and flexor torque characteristics before and after unilateral total knee arthroplasty. *Am J Phys Med Rehabil*. 2006;85:737–746.

10 Minns Lowe CJ, Barker KL, Dewey M, Sackley CM. Effectiveness of physiotherapy exercise after knee arthroplasty for osteoarthritis: systematic review and meta-analysis of randomised controlled trials. *BMJ*. 2007;335:812.

11 Meier W, Mizner RL, Marcus RL, et al. Total knee arthroplasty: muscle impairments, functional limitations, and recommended rehabilitation approaches. *J Orthop Sports Phys Ther*. 2008;38:246–256.

12 Yoshida Y, Mizner RL, Ramsey DK, Snyder-Mackler L. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. *Clin Biomech (Bristol, Avon)*. 2008;23:320–328.

13 Finch E, Walsh M, Thomas SG, Woodhouse LJ. Functional ability perceived by individuals following total knee arthroplasty compared to age-matched individuals without knee disability. *J Orthop Sports Phys Ther*. 1998;27:255–263.

14 Lorentzen JS, Petersen MM, Brot C, Madsen OR. Early changes in muscle strength after total knee arthroplasty: a 6-month follow-up of 30 knees. *Acta Orthop Scand*. 1999;70:176–179.

15 Ouellet D, Moffet H. Locomotor deficits before and two months after knee arthroplasty. *Arthritis Rheum*. 2002;47:484–493.

16 Rossi MD, Hasson S. Lower-limb force production in individuals after unilateral total knee arthroplasty. *Arch Phys Med Rehabil*. 2004;85:1279–1284.

17 Berman AT, Bosacco SJ, Israelite C. Evaluation of total knee arthroplasty using isokinetic testing. *Clin Orthop Relat Res*. 1991;(271):106–113.

18 Rodgers JA, Garvin KL, Walker CW, et al. Preoperative physical therapy in primary total knee arthroplasty. *J Arthroplasty*. 1998;13:414–421.

19 Gapeyeva H, Buht N, Peterson K, et al. Quadriceps femoris muscle voluntary isometric force production and relaxation characteristics before and 6 months after unilateral total knee arthroplasty in women. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:202–211.

20 Huang CH, Cheng CK, Lee YT, Lee KS. Muscle strength after successful total knee replacement: a 6- to 13-year follow-up. *Clin Orthop Relat Res*. 1996;(328):147–154.

21 Berth A, Urbach D, Awiszus F. Improvement of voluntary quadriceps muscle activation after total knee arthroplasty. *Arch Phys Med Rehabil*. 2002;83:1432–1436.

22 Silva M, Shepherd EF, Jackson WO, et al. Knee strength after total knee arthroplasty. *J Arthroplasty*. 2003;18:605–611.

23 Perhonen M, Komi P, Häkkinen K, et al. Strength training and neuromuscular function in elderly people with total knee endoprosthesis. *Scand J Med Sci Sports*. 1992;2:234–243.

24 Mizner RL, Petterson SC, Stevens JE, et al. Early quadriceps strength loss after total knee arthroplasty: the contributions of muscle atrophy and failure of voluntary muscle activation. *J Bone Joint Surg Am*. 2005;87:1047–1053.

25 Portegijs E, Sipilä S, Alen M, et al. Leg extension power asymmetry and mobility limitation in healthy older women. *Arch Phys Med Rehabil*. 2005;86:1838–1842.

26 Portegijs E, Sipilä S, Pajala S, et al. Asymmetrical lower extremity power deficit as a risk factor for injurious falls in healthy older women. *J Am Geriatr Soc*. 2006;54:551–553.

27 Lamb SE, Morse RE, Evans JG. Mobility after proximal femoral fracture: the relevance of leg extensor power, postural sway and other factors. *Age Ageing*. 1995;24:308–314.

28 Skelton DA, Kennedy J, Rutherford OM. Explosive power and asymmetry in leg muscle function in frequent fallers and non-fallers aged over 65. *Age Ageing*. 2002;31:119–125.

29 Portegijs E, Sipilä S, Rantanen T, Lamb SE. Leg extension power deficit and mobility limitation in women recovering from hip fracture. *Am J Phys Med Rehabil*. 2008;87:363–370.

30 Sipilä S, Suominen H. Effects of strength and endurance training on thigh and leg muscle mass and composition in elderly women. *J Appl Physiol*. 1995;78:334–340.

31 Thelen DG, Schultz AB, Alexander NB, Ashton-Miller JA. Effects of age on rapid ankle torque development. *J Gerontol A Biol Sci Med Sci*. 1996;51:M226–M232.

32 Thelen DG, Muriuki M, James J, et al. Muscle activities used by young and old adults when stepping to regain balance during a forward fall. *J Electromyogr Kinesiol*. 2000;10:93–101.

33 Robinovitch SN, Hsiao ET, Sandler R, et al. Prevention of falls and fall-related fractures through biomechanics. *Exerc Sport Sci Rev*. 2000;28:74–79.

34 Suetta C, Aagaard P, Magnusson SP, et al. Muscle size, neuromuscular activation, and rapid force characteristics in elderly men and women: effects of unilateral long-term disuse due to hip-osteoarthritis. *J Appl Physiol*. 2007;102:942–948.

35 Frontera WR, Hughes VA, Fielding RA, et al. Aging of skeletal muscle: a 12-yr longitudinal study. *J Appl Physiol*. 2000;88:1321–1326.

36 Frontera WR, Meredith CN, O'Reilly KP, et al. Strength conditioning in older men: skeletal muscle hypertrophy and improved function. *J Appl Physiol*. 1988;64:1038–1044.

37 Rantanen T, Avela J. Leg extension power and walking speed in very old people living independently. *J Gerontol A Biol Sci Med Sci*. 1997;52:M225–M231.

38 Bean JF, Kiely DK, Herman S, et al. The relationship between leg power and physical performance in mobility-limited older people. *J Am Geriatr Soc*. 2002;50:461–467.

39 Herman S, Kiely DK, Leveille S, et al. Upper and lower limb muscle power relationships in mobility-limited older adults. *J Gerontol A Biol Sci Med Sci*. 2005;60:476–480.

III

EFFECTS OF AQUATIC RESISTANCE TRAINING ON MOBILITY LIMITATION AND LOWER LIMB IMPAIRMENTS AFTER KNEE REPLACEMENT (ISRCTN50731915)

by

Valtonen A, Pöyhönen T, Sipilä S, Heinonen A. 2010

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ORIGINAL ARTICLE

Effects of Aquatic Resistance Training on Mobility Limitation and Lower-Limb Impairments After Knee Replacement

Anu Valtonen, MSc, Tapani Pöyhönen, PhD, Sarianna Sipilä, PhD, Ari Heinonen, PhD

ABSTRACT. Valtonen A, Pöyhönen T, Sipilä S, Heinonen A. Effects of aquatic resistance training on mobility limitation and lower-limb impairments after knee replacement. Arch Phys Med Rehabil 2010;91:833-9.

Objective: To study the effects of aquatic resistance training on mobility, muscle power, and cross-sectional area.

Design: Randomized controlled trial.

Setting: Research laboratory and hospital rehabilitation pool.

Participants: Population-based sample (N=50) of eligible women and men 55 to 75 years old 4 to 18 months after unilateral knee replacement with no contraindications who were willing to participate in the trial.

Interventions: Twelve-week progressive aquatic resistance training (n=26) or no intervention (n=24).

Main Outcome Measures: Mobility limitation assessed by walking speed and stair ascending time, and self-reported physical functional difficulty, pain, and stiffness assessed by Western Ontario and McMaster University Osteoarthritis Index (WOMAC) questionnaire. Knee extensor power and knee flexor power assessed isokinetically, and thigh muscle cross-sectional area (CSA) by computed tomography.

Results: Compared with the change in the control group, habitual walking speed increased by 9% (*P*=.005) and stair ascending time decreased by 15% (*P*=.006) in the aquatic training group. There was no significant difference between the groups in the WOMAC scores. The training increased knee extensor power by 32% (*P*<.001) in the operated and 10% (*P*=.001) in the nonoperated leg, and knee flexor power by 48% (*P*=.003) in the operated and 8% (*P*=.002) in the nonoperated leg compared with controls. The mean increase in thigh muscle CSA of the operated leg was 3% (*P*=.018) and that of the nonoperated leg 2% (*P*=.019) after training compared with controls.

Conclusions: Progressive aquatic resistance training had favorable effects on mobility limitation by increasing walking speed and decreasing stair ascending time. In addition, training increased lower limb muscle power and muscle CSA. Resistance training in water is a feasible mode of rehabilitation that has wide-ranging positive effects on patients after knee replacement surgery.

Key Words: Osteoarthritis; Rehabilitation; Water.

KNEE REPLACEMENT effectively reduces pain[1-3] and decreases perceived disability.[4,5] Nevertheless, persons with knee replacement report more disabilities than do healthy controls matched for age and sex.[6,7] One reason for the greater prevalence of disability of persons with knee replacement is difficulty in mobility-related tasks requiring muscle power such as walking, negotiating stairs, and other physical abilities.[8-14] Mobility limitations are associated with decreased lower limb muscle strength and power.[10,11,14] Earlier studies have shown that knee extensor and flexor muscle weakness continues to persist for several months, even years, postoperatively compared with the nonoperated side[8,12,14-19] or with healthy controls.[8,17,18,20,21] Our previous study showed that in persons with knee replacement, the mean asymmetric power deficit was 19% to 23% in the knee flexor and extensor muscles and 14% in knee extensor muscle mass on average 10 months postsurgery.[19] Factors leading to muscle weakness include the loss of muscle tissue because of long-term disuse of the affected leg prior to the operation,[22] procedures related to the operation,[18] and lack of postoperative strength–increasing rehabilitation.[23]

Aquatic training has been well studied in healthy people and people with knee or hip osteoarthritis with mostly positive results on mobility,[24-26] muscle strength,[24-28] or muscle mass.[27] The effects of aquatic training after knee replacement surgery have been less investigated. Two recent studies found no aquatic rehabilitation effect on mobility when the rehabilitation programs started less than 2 weeks[29,30] after knee replacement surgery. However, it has been reported[29] that 2 weeks of aquatic rehabilitation commencing 4 days after knee replacement increased hip abduction and knee extension strength compared with the ward physiotherapy. However, the training programs lasted only 2 weeks[29] or comprised traditional aquatic exercise without additional resistance.[30]

Persons with knee replacement have long-term muscle weakness and mobility limitation. It is unclear, however, whether these potential risk factors for disability can be affected by progressive aquatic resistance training. Therefore, the purpose of this randomized

List of Abbreviations

CI	confidence interval
CSA	cross-sectional area
CT	computed tomography
ICC	intraclass correlation coefficient
RPE	Rating of Perceived Exertion
WOMAC	Western Ontario and McMaster University Osteoarthritis Index

From Department of Health Sciences (Valtonen, Heinonen) and Finnish Centre for Interdisciplinary Gerontology (Sipilä), University of Jyväskylä, Jyväskylä; Rehabilitation and Pain Unit, Kymenlaakso Central Hospital, Kotka (Valtonen, Pöyhönen), Finland.

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Reprint requests to Anu Valtonen, MSc, Dept of Health Sciences, University of Jyväskylä, PO Box 35, FI-40014 University of Jyväskylä, Finland, e-mail: *anu.m.valtonen@jyu.fi*.

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controlled study was to investigate the effects of progressive aquatic resistance training on mobility, muscle power, and muscle CSA in women and men 55 to 75 years old after knee replacement surgery. Our hypothesis was that aquatic resistance training increases muscle power of the operated and nonoperated side and reduces mobility limitation among older persons with knee replacement.

METHODS

Setting and Participants

In 2005, all 201 patients who according to the physical therapy records of Kymenlaakso Central Hospital had undergone unilateral knee replacement 4 to 18 months prior to the study were informed about the study. Eighty-six patients responded and were contacted by the research personnel and interviewed over the telephone. Patients with bilateral knee arthroplasty, revision arthroplasty, severe cardiovascular diseases, dementia, rheumatoid arthritis, or any major surgery in either of the knees were excluded from the study. Thus, 50 eligible volunteers (age range, 55–75y), 30 women and 20 men, were randomly assigned after the baseline measurements into an aquatic resistance training group (16 women, 10 men) and a control group (14 women, 10 men). The random allocation was concealed in sealed envelopes in blocks of sex, age, and type of knee replacement. The intervention profile is displayed in figure 1.

The reason for the knee replacement surgery for all the participants was knee joint osteoarthritis. Details of the knee replacement operation were collected from the hospital medical records. In all cases, the knee replacement surgery had been performed with cement fixation (48 with tricompartmental total knee arthroplasty, 2 with unicompartmental hemiarthroplasty). The participants with hemiarthroplasty did not differ from those with total knee replacement in any of the variables.

Before the laboratory examinations, the participants were informed about the study, and they gave their written informed consent. The study was conducted according to the Declaration of Helsinki and approved by the ethical committee of Kymenlaakso Central Hospital.

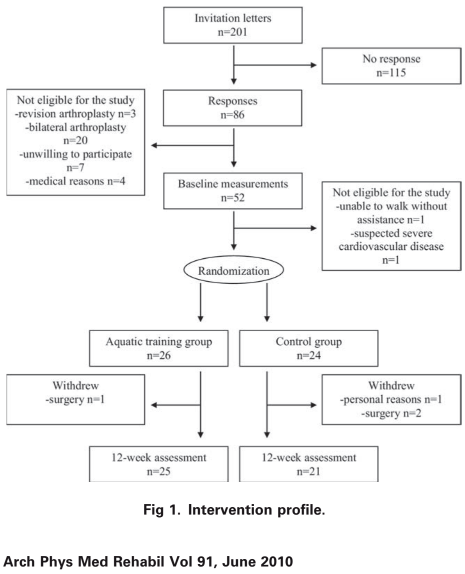

Fig 1. Intervention profile.

Measurements

Quantitative CT measurements and analyses were conducted blind to the study group. The other measurements were conducted unblind.

Health Status

The general health, clinical history, medication, and diseases of the participants were assessed by a physician before the laboratory examinations to evaluate potential contraindications for safe participation in the measurements and training. Body height and weight were measured in the laboratory using standard procedures. The presence of self-reported chronic conditions was recorded by a questionnaire. Habitual physical activity was recorded during the intervention using a training diary.

Mobility Limitation as a Primary Outcome

Mobility limitation was assessed by maximal and habitual walking speed and stair ascending time.

Maximal and habitual walking speed. Maximal[31] and habitual[32] walking speed over 10m were measured in the hospital corridor, and the time taken was recorded using photocells.[a] First, the participants were instructed to walk at their habitual walking speed. Second, they were instructed to walk as fast as possible without compromising their safety. All the participants wore thin aquatic shoes and were allowed 3m for acceleration. Each participant performed 2 trials at maximal and 2 at habitual walking speed separated by a 1-minute rest, and the faster performances were accepted as the results. In our laboratory, the ICC for persons with knee replacement has been .86 for maximal and .44 for habitual walking speed.[19]

Ascending stairs. Maximal time taken to ascend 10 stairs was measured in the hospital corridor,[33] and the time taken was recorded using photocells.[a] The stair height was 17cm and depth 29.5cm. The participants were instructed to step alternately on each stair and ascend as fast as possible without compromising their safety. Using a handrail or taking a step with both feet on the same step (bipedal ascent) was allowed only if necessary. Each participant performed 2 ascents separated by a 1-minute rest. The time of the faster performance was accepted as the result. The ICC for ascending stairs for persons with knee replacement has been .73.[19]

Self-Reports

The WOMAC questionnaire,[34] a self-rated measure of pain and stiffness and the physical functional difficulty of the participants, is widely used after joint replacement surgery research.[29,35] The version based on the visual analog scale (range, 0–100mm, with 100 indicating the worst possible situation) was used. In the physical functional difficulty score, 80% of the participants did not answer the subscale "getting in and out of the bath" because they did not have a bath. Therefore, this subscale was not included in the analysis.

Lower-Extremity Impairments of the Operated and Nonoperated Side

Muscle power. Maximal muscle power of the knee extensors and flexors was measured with an isokinetic dynamometer[b] with a sampling frequency of 100Hz and measurement error of 1% throughout the entire range of motion.[27] The dynamometer was calibrated before each measurement session according to the procedure recommended by the manufacturer. Before the measurement session, the participants were carefully familiarized with the testing procedure. For each leg, the axis of rotation of the dynamometer was aligned with the condylus femoris lateralis. The lever arm of the dynamometer was attached around the ankle 2.5cm above the midpoint of the malleolus lateralis. Hip and thigh were stabilized with straps. The measurement was performed on as large a range of motion of the knee as possible. The nonoperated leg was measured first. After 2 to 3 submaximal flexion-extension movements, 5 maximal continuous flexion-extension trials were performed at an angular velocity of 180°/s. The participants were verbally encouraged to make a maximal effort throughout the whole range of motion. Peak knee extensor and flexor power (W) values were analyzed from the best extension and flexion efforts. The ICC of the isokinetic parameters for persons with knee replacement was between .90 and .96 for the operated knee.[19]

Muscle CSA. Quantitative CT scans were obtained from both midthighs using a Siemens Somatom DR Scanner[c] with the patient in a supine position.[36] Midthigh was defined as the midpoint between the level of the greatest lateral protuberance of the greater trochanter and lower edge of the patella. The scans were analyzed to measure thigh muscle CSA (cm^2)[36] using software developed for the purpose at the University of Jyväskylä.[d] The software separates fat and lean tissue on the basis of radiologic tissue density (measured as attenuation in Hounsfield units) limits. In our previous study, the coefficient of variation was calculated between 2 consecutive repeated measurements and was 1% to 2% for muscle CSA.[36]

Intervention

Exercise sessions were conducted twice a week in small classes containing 4 to 5 persons. All the classes were supervised by an experienced physiotherapist. Table 1 summarizes the training program, including the weekly sets, duration of work, rest, and the training load produced by the resistance boots as well as the mean RPE value for each week.

Each session started with an 8-minute warm-up including walking (forward, backward, and sideways), aqua jogging, and lower-leg muscle stretching. This was followed by 30 to 40 minutes of resistance training and a 5-minute cooling down period. The exercises were selected on the basis of our previous study.[27] Each training session consisted of 5 exercises for both legs: (1) knee extension-flexion movement in a sitting position, (2) hip abduction-adduction with extended knee in a standing position, (3) hip extension-flexion with extended knee in a standing position, (4) knee extension-flexion in a standing position, and (5) step-squat backward from the aqua aerobic step board. The subjects were verbally encouraged to perform each repetition with maximal effort in order to achieve the highest possible movement velocity and resistance. In each exercise, the operated leg was trained first and then the nonoperated leg. The operated leg was trained to 30% more sets compared with the nonoperated one. The participants were asked to describe their perceived exertion after each exercise with the RPE scale (range, 6–20).[37] The participants were asked to report whether they had any pain or discomfort during the training sessions.

The progression of the exercise program was ensured by using resistance boots of different sizes and by varying the amount and duration of sets. The first 2 weeks of training were conducted without resistance boots in order to adapt to the exercises. The actual training was conducted using small Aqua Runner Zero Impact Footwear[e] (2 weeks) and with medium (4 weeks) and large resistance boots[f] (4 weeks). In weeks 7 and 12, one training session was conducted without resistance boots in order to avoid overtraining. The frontal area of the medium size resistance boots was $0.045m^2$ and that of the large resistance boots, $0.075m^2$. The small footwear was attached around the foot and the medium and large boots around the lower leg and foot during the exercises. In our previous study,[27] the drag during the exercises in healthy women was double with the medium boots and triple with the large boots compared with the barefoot condition.

Intensity of training was estimated for 3 women and 3 men in the training group (mean age ± SD, 62.2±4.3y; mean height ± SD, 169.8±8.2cm; mean weight ± SD, 86.3±9.2kg) by the RPE scale and with heart rate monitoring. The average heart rates were recorded with the Polar RS400 heart rate monitor[g] during the 5 exercises, excluding the warm-up and cool-down. Age-related maximal heart rates were calculated according to the following equation: 220–age (y). Among the 6 persons tested for training intensity, the mean RPE value ± SD during the exercises was 17±1 (range, 14–18). The mean heart rate ± SD was 116±18 beats/s (range, 93–148), which was 73% of

Table 1: Summary of the Aquatic Training Protocol

Week	Sets		Repetitions/Set	Work/Set (s)	Rest/Set (s)	Resistance	Mean RPE
	Operated	Nonoperated					
1	2	2	25–30	45	30	No boots	14
2	2	2	25–30	45	30	No boots	15
3	2	2	20–25	35	30	Small	16
4	3	2	20–25	35	30	Small	16
5	2	2	14–20	30	30	Medium	16
6	2	2	14–20	30	30	Medium	17
7	3	2	25–30	40	30	No boots	16
	3	2	14–20	30	30	Medium	16
8	3	2	14–20	30	30	Medium	17
9	2	2	12–15	30	30	Large	17
10	3	2	12–15	30	40	Large	16
11	4	2	12–15	30	40	Large	17
12	3	2	12–15	30	40	Large	17
	3	2	25–30	30	40	No boots	16

NOTE. Training was conducted 2 times a week. Weeks 7 and 12 were conducted with 2 different training sessions: one with resistance boots and one without extra resistance. During weeks 1 to 6 and weeks 8 to 11, the 2 training sessions were similar.

the age-related maximal heart rate. In the hydroboot conditions, the movement velocities were slower and the number of repetitions a set lower but the resistance higher compared with the barefoot condition.[27,38]

Control Group

The control group did not receive any intervention. Participants were encouraged to continue their lives as usual and maintain their habitual level of physical activity during the trial.

Statistical Analysis

Means and SDs were calculated. The data obtained from men and women were pooled to obtain a larger sample size because there were no differences between the sexes in age, postoperation time, or training response. All the analyses were based on an intention-to-treat analysis. Participants with missing variables in the muscle power tests (1 because of pain in the knee, 2 because of technical problems) or in the CT measurement (3 because of technical problems) were omitted only from the analysis in question.

All the variables were normally distributed; therefore, the analysis of covariance was used to assess the training effects between the training and control groups. Age, sex, postoperative time, and training compliance were tested separately and together as covariates. Because they did not have an influence on the results, only the baseline measurement was used as covariate.

Training compliance in the training sessions was calculated for each participant according to the following equation:

$$(\text{attended}/\text{offered}) \times 100\%$$

The relative change in mobility, WOMAC scores, muscle power, and muscle CSA measures between the pretrial and posttrial measurements was calculated as

$$(\text{post–pre})/\text{pre} \times 100\%$$

The differences (effects) between the mean relative changes in the study groups and the 95% CIs of the difference were also calculated. Ninety percent CI of the minimal detectable change for the absolute differences between the groups was calculated as

$$\text{SEM} \times z \times \sqrt{2}$$

to assess clinically significant differences.

All the eligible patients with knee replacement were included in the study and thus, with the present dropout rate, the sample size of the study provided 80% statistical power to detect a difference of about 10% between the groups in habitual walking speed at a significance level of P less than .05.

RESULTS

Baseline Characteristics

Table 2 shows the baseline physical characteristics of the training and control groups. No between-group differences were observed at baseline.

Program Feasibility

The dropout rate was 6%. In the training group, 1 participant (knee replacement operation on the other knee), and in the control group, 3 participants (1 for personal reasons and 2 for a knee replacement operation on the other knee) were lost to follow-up (see fig 1). Training compliance in the aquatic training sessions was excellent, averaging 98% (590 sessions attended/600 offered). In the training group, the participants did not report any pain during the training program. However, 1 participant visited the study physician because of elevated blood pressure without taking further actions or a pause in the training regimen. The mean RPE value for training was 16 (range, 14–17).

Table 2: Baseline Physical Characteristics of the Participants in the Aquatic Training and Control Group

Characteristics	Aquatic Training Group n=26	Control Group n=24
Age (y)	66.2±6.3	65.7±6.0
Weight (kg)	83.2±15.2	83.9±15.0
Height (cm)	167.3±9.3	169.7±8.2
Time since operation (mo)	9.9±4.7	9.2±4.2
Comorbidities,* n (%)		
Cardiovascular	15 (58)	9 (38)
Endocrine	2 (8)	2 (8)
Musculoskeletal	13 (50)	8 (33)
Respiratory	2 (8)	1 (4)
Diagnosed knee osteoarthritis of the nonoperated knee, n (%)	4 (15)	4 (17)

NOTE. Values are mean ± SD unless indicated otherwise.
*Self-reported number of comorbidities.

Mobility Limitation

At baseline, there were no differences between the aquatic training and the control group in maximal walking speed (P=.214), habitual walking speed (P=.684), or stair ascending time (P=.884). In the baseline measurements, 3 participants in the training and 1 in the control group were unable to perform alternate stepping and thus used bipedal ascent.

Compared with controls, the training group showed a mean increase in their habitual walking speed of 9% (95% CI, 3%–15%) at the end of the intervention. Maximal walking speed was not affected by training (1%; 95% CI, −6% to 8%). Stair ascending time decreased significantly among the trainees compared with controls (−15%; 95% CI, −24% to −6%). After the intervention, 1 participant in each group used bipedal ascent.

Self-Reports

At baseline, there were no differences between the aquatic training and control group in the WOMAC physical functional difficulty (P=.109), pain (P=.866), or stiffness (P=.254) scores. The scores for physical functional difficulty (analysis of covariance, P=.197), pain (P=.352), and stiffness (P=.097) in the operated knee were not affected by training.

Lower-Extremity Impairments

At baseline, there were no differences between the aquatic training and the control group in knee extension power (P=.440) or knee flexion power (P=.430) on the operated side, or in knee extension power (P=.974) or knee flexion power (P=.734) on the nonoperated side. In addition, thigh muscle CSA did not differ between the groups at baseline in the operated (P=.657) or nonoperated leg (P=.693).

The mean gain in knee extension power was significantly greater in both the operated (effect 32%; 95% CI, 18%–47%) and nonoperated leg (10%; 95% CI, 5%–16%) in the training group compared with controls. Compared with controls, a significant increase was also observed in knee flexion power in the operated (48%; 95% CI, 8%–89%) and in the nonoperated leg (8%; 95% CI, 2%–14%) in the training group. A small but

Table 3: Effects of Aquatic Training (Mean ± SD, Mean Difference, and 95% CI)

	Aquatic Training Group				Control Group					
	Baseline		Posttrial		Baseline		Posttrial			
Variable	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	Mean Difference[†] (95% CI)	ANCOVA P[‡]
KEP operated (W)	23	112.6±51.4	23	145.6±64.0	20	129.7±47.3	20	129.3±44.8	33.5* (17.7 to 49.3)	<.001
KEP nonoperated (W)	23	153.6±50.9	23	172.3±60.0	20	158.4±57.2	20	160.4±56.9	16.9* (7.2 to 26.6)	.001
KFP operated (W)	23	99.8±49.4	23	135.9±60.0	20	116.0±42.9	20	117.8±41.3	32.3* (11.6 to 53.0)	.003
KFP nonoperated (W)	24	130.2±44.1	24	144.2±53.6	20	141.0±50.9	20	143.4±51.8	12.6* (5.0 to 20.2)	.002
CSA operated (cm^2)	24	105.2±30.0	24	110.1±30.7	19	101.5±21.1	19	103.5±20.2	3.0* (0.5 to 5.4)	.018
CSA nonoperated (cm^2)	24	114.5±29.1	24	117.6±39.3	19	111.1±25.4	19	112.0±24.6	2.2* (0.4 to 4.1)	.019
Maximal walking speed (m/s)	25	1.90±0.30	25	1.96±0.31	21	1.84±0.53	21	1.87±0.52	0.04 (−0.08 to 0.16)	.532
Habitual walking speed (m/s)	25	1.31±0.17	25	1.41±0.24	21	1.30±0.24	21	1.29±0.26	0.12* (0.04 to 0.20)	.005
Stair ascending (s)	25	4.96±2.10	25	4.27±1.67	21	4.68±1.81	21	4.71±1.74	−0.66* (−1.12 to −0.20)	.006
WOMAC total score[§] (mm)	25	22.4±10.6	25	17.9±8.5	21	18.1±11.6	21	18.3±16.0	−4.1 (−9.1 to 1.0)	.110
Pain score[‖] (mm)	25	16.8±10.6	25	13.0±8.7	21	17.0±14.6	21	15.5±12.4	−2.4 (−7.4 to 2.7)	.352
Stiffness score[‖] (mm)	25	32.7±24.0	25	25.9±20.6	21	26.1±19.3	21	30.3±25.5	−8.9 (−19.5 to 1.7)	.097
Physical functional difficulty score[‖] (mm)	25	22.6±11.7	25	18.5±9.4	21	17.0±11.5	21	17.3±17.2	−3.6 (−9.3 to 2.1)	.212

Abbreviations: ANCOVA, analysis of covariance; CSA, cross-sectional area; KEP, knee extension power; KFP, knee flexion power; VAS, visual analog scale.
*Clinically significant difference between the groups. Assessed by minimal detectable change at the 90% confidence level, calculated for the absolute mean difference (effect) between the groups as $SEM \times z \times \sqrt{2}$.
[†]Mean difference (effect) calculated as the absolute mean difference (95% CI) between the study groups.
[‡]Derived from ANCOVA, baseline as covariate.
[§]Total score of WOMAC questionnaire based on VAS.
[‖]Assessed with WOMAC questionnaire, subscales of pain, stiffness and physical functional difficulty based on VAS.

significant increase in thigh muscle CSA in the operated (3%; 95% CI, 0%–5%) and in the nonoperated leg (2%; 95% CI, 0%–3%) was observed in the training group compared with the control group (table 3).

DISCUSSION

The results of this study support our hypothesis and show that 12 weeks of progressive aquatic resistance training decreased mobility limitation in women and men 55 to 75 years old after unilateral knee replacement. In addition, knee extensor and flexor power and thigh muscle CSA increased with training, especially in the operated leg.

Our results showed training effects in the operated knee of 32% and 48% for knee extensor and flexor power, respectively. The corresponding values for the nonoperated side were 8% and 10%. The greater improvement in the operated leg was expected because the operated leg received 30% more training than the nonoperated one. The operated leg was also weaker at the baseline measurements. The training effect for the nonoperated knee was in line with the values from 6% to 13% reported in earlier studies on aquatic resistance training in healthy adults and older persons.[25,27,28] Earlier studies in subjects with hip or knee osteoarthritis have reported mixed results of the effects of aquatic exercise on the muscle strength of the lower limbs.[24,26,39,40] In persons with osteoarthritis, pain in the impaired joint can affect training intensity. In addition, in earlier studies the training programs lasted for only 6 weeks[24] or did not include extra resistance.[26,39] However, after knee replacement, when the joint is pain-free, a training effect seems to be evident, as found in our study. This was also found in the earlier study,[29] which reported that 2 weeks of aquatic rehabilitation commencing 4 days after knee replacement increased hip abduction and knee extension strength compared with the ward physiotherapy.

The muscle CSA results of this study are in line with those of our previous study,[27] which showed an increase of 4% to 5% in extensor and flexor muscle CSA in healthy women after aquatic training. Muscle hypertrophy is one of the mechanisms underlying increasing muscle strength during training. However, as has been suggested by earlier studies in healthy older persons, the increase in muscle mass induced by resistance training is much less than the increase in muscle strength,[41-43] as was also seen in this study. An increase in muscle mass also has important advantages other than increased force production. Muscle tissue acts as a dynamic metabolic store, as a vital source of heat, and as protective padding for the skeleton against falls.[44]

Our 12-week aquatic resistance training program was specifically targeted at improving lower extremity muscle power and mass, and thus mobility. Aquatic resistance training increased habitual walking speed and stair ascending time compared with controls. However, maximal walking speed was not affected by the training, which may be a result of the relatively fast walking speed (1.9m/s) of the participants at the baseline. In earlier studies, aquatic training with or without additional resistance has shown favorable effects in the mobility in healthy older women[25] and in persons with osteoarthritis.[24,26] In addition, 2 earlier studies have been reported on the effects of 2 to 6 weeks of aquatic exercise intervention compared with dry-land rehabilitation[30] or with ward control[29] on mobility among people recovering from knee replacement surgery. In the recovery phase (<2wk postsurgery), mobility increased equally in all study groups with no between-group differences. However, the operated side would appear to remain weaker for years compared with the nonoperated side or with healthy controls, suggesting increased risk for mobility limitation after knee replacement. Our encouraging results in habitual walking speed and stair ascending may be a result of the progressive extra resistance produced by the resistance boots during the training. In addition, the result may partly be a result of the low base level of functional ability and muscle power of the older people with knee replacement surgery, which is impaired, at least partly, by pain and long-term disuse before the operation and for up to months afterward.

In an earlier study, an 8-week intensive functional dry-land rehabilitation program after knee replacement decreased self-reported physical functional difficulty.[35] No group differences in the WOMAC physical functional difficulty were found after a 6-week water-based and dry-land rehabilitation program commencing 2 weeks after knee replacement.[30] In the present study, the training had no effect on the self-reported physical functional difficulty compared with controls. This might be a result of the relative good health of the study population, who did not appear to have problems with the simpler tasks, such as lying in bed and sitting. Training also had no effect on pain, which was expected because of the relatively small pain scores at baseline, as also found after knee replacement in other studies.[35,45,46]

Our 12-week aquatic resistance training program induced marked improvements in lower-extremity muscle power and mass, and thus mobility, in persons with a knee replacement operation 4 to 18 months earlier. The training program was not started right after the operation, which is the usual course in rehabilitation practice. The results indicate that it would be important to offer rehabilitative exercise strategies for the patients with joint replacement in the long run and not only for the very acute phase.

All in all, the marked improvements in muscle power and mobility in our study might be a result of the use of an effective and safe training medium, water. Water minimizes the effects of gravity, which reduces compressive and shear forces on joints and thus offers a comfortable training medium for patients with musculoskeletal problems. In addition, water offers variable, easily individually adjustable resistance to movements. The resistance offered by water to movements increases with speed: the drag produced by water quadruples when velocity doubles.[27] Thus, progressive resistance-type aquatic training seems to lead to both functional and structural adaptations in the neuromuscular system. Therefore, progressive aquatic training with resistance boots can be recommended in rehabilitation for patients with knee replacement.

Study Limitations

This study has some limitations. We have made multiple comparisons in these data, and it is possible that there is a study-wide type I error. However, in randomized controlled trials with selected and preplanned main outcome, correction of multiple comparisons is unnecessary. We were not able to conduct complete blinding, which thus limits the strength of the conclusions. Unfortunately, we did not know the preoperative impairment or level of mobility limitation of the participants or the rehabilitation before the baseline measurements. However, the randomization, at least in part, reduced this potential bias. In addition, the intensity of training was challenging to define. Even though the subjects were encouraged to exercise with maximal effort, we do not know whether they exercised to fatigue. This study has several strengths. First, it was a randomized controlled trial with both training and control groups, and with only a very few dropouts. Second, the trainees performed the training protocol with a high compliance (98%) and did not report any pain during training. Third, the recruitment of the participants was population-based, and the study groups were homogeneous. In the future, the intensive training program with mixed aquatic and dry-land training program should be considered.

CONCLUSIONS

The results of this randomized controlled trial showed that 12 weeks of progressive aquatic training reduced mobility limitation in persons with knee replacement. Knee extensor and flexor power and thigh muscle CSA increased with training, especially in the operated leg. The aquatic training was well tolerated, and thus water would appear to offer an effective environment for training muscle power and mobility after knee replacement.

References

1. Martin SD, Scott RD, Thornhill TS. Current concepts of total knee arthroplasty. J Orthop Sports Phys Ther 1998;28:252-61.
2. NIH Consensus Panel. NIH consensus statement on total knee replacement December 8-10, 2003. J Bone Joint Surg Am 2004; 86-A:1328-35.
3. Jones DL, Westby MD, Greidanus N, et al. Update on hip and knee arthroplasty: current state of evidence. Arthritis Rheum 2005;53:772-80.
4. Jones CA, Voaklander DC, Johnston DW, Suarez-Almazor ME. Health related quality of life outcomes after total hip and knee arthroplasties in a community based population. J Rheumatol 2000;27:1745-52.
5. Fitzgerald JD, Orav EJ, Lee TH, et al. Patient quality of life during the 12 months following joint replacement surgery. Arthritis Rheum 2004;51:100-9.
6. Finch E, Walsh M, Thomas SG, Woodhouse LJ. Functional ability perceived by individuals following total knee arthroplasty compared to age-matched individuals without knee disability. J Orthop Sports Phys Ther 1998;27:255-63.
7. Noble PC, Gordon MJ, Weiss JM, Reddix RN, Conditt MA, Mathis KB. Does total knee replacement restore normal knee function? Clin Orthop Relat Res 2005;431:157-65.
8. Walsh M, Woodhouse LJ, Thomas SG, Finch E. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. Phys Ther 1998;78:248-58.
9. Lamb SE, Frost H. Recovery of mobility after knee arthroplasty: expected rates and influencing factors. J Arthroplasty 2003;18: 575-82.
10. Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. J Orthop Sports Phys Ther 2005;35:424-36.
11. Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. J Orthop Res 2005;23:1083-90.
12. Rossi MD, Brown LE, Whitehurst M. Knee extensor and flexor torque characteristics before and after unilateral total knee arthroplasty. Am J Phys Med Rehabil 2006;85:737-46.
13. Minns Lowe CJ, Barker KL, Dewey M, Sackley CM. Effectiveness of physiotherapy exercise after knee arthroplasty for osteoarthritis: systematic review and meta-analysis of randomised controlled trials. BMJ 2007;335:812.
14. Yoshida Y, Mizner RL, Ramsey DK, Snyder-Mackler L. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. Clin Biomech (Bristol, Avon) 2008;23:320-8.
15. Rodgers JA, Garvin KL, Walker CW, Morford D, Urban J, Bedard J. Preoperative physical therapy in primary total knee arthroplasty. J Arthroplasty 1998;13:414-21.
16. Lorentzen JS, Petersen MM, Brot C, Madsen OR. Early changes in muscle strength after total knee arthroplasty: a 6-month follow-up of 30 knees. Acta Orthop Scand 1999;70:176-9.
17. Rossi MD, Hasson S. Lower-limb force production in individuals after unilateral total knee arthroplasty. Arch Phys Med Rehabil 2004;85:1279-84.

18. Gapeyeva H, Buht N, Peterson K, Ereline J, Haviko T, Paasuke M. Quadriceps femoris muscle voluntary isometric force production and relaxation characteristics before and 6 months after unilateral total knee arthroplasty in women. Knee Surg Sports Traumatol Arthrosc 2007;15:202-11.
19. Valtonen A, Poyhonen T, Heinonen A, Sipila S. Muscle deficits persist after unilateral knee replacement and have implications for rehabilitation. Phys Ther 2009;89:1072-9.
20. Huang CH, Cheng CK, Lee YT, Lee KS. Muscle strength after successful total knee replacement: a 6- to 13-year followup. Clin Orthop Relat Res 1996;328:147-54.
21. Silva M, Shepherd EF, Jackson WO, Pratt JA, McClung CD, Schmalzried TP. Knee strength after total knee arthroplasty. J Arthroplasty 2003;18:605-11.
22. Suetta C, Aagaard P, Magnusson SP, et al. Muscle size, neuromuscular activation, and rapid force characteristics in elderly men and women: effects of unilateral long-term disuse due to hip-osteoarthritis. J Appl Physiol 2007;102:942-8.
23. Suetta C, Andersen JL, Dalgas U, et al. Resistance training induces qualitative changes in muscle morphology, muscle architecture, and muscle function in elderly postoperative patients. J Appl Physiol 2008;105:180-6.
24. Foley A, Halbert J, Hewitt T, Crotty M. Does hydrotherapy improve strength and physical function in patients with osteoarthritis—a randomised controlled trial comparing a gym based and a hydrotherapy based strengthening programme. Ann Rheum Dis 2003;62:1162-7.
25. Tsourlou T, Benik A, Dipla K, Zafeiridis A, Kellis S. The effects of a twenty-four-week aquatic training program on muscular strength performance in healthy elderly women. J Strength Cond Res 2006;20:811-8.
26. Hinman RS, Heywood SE, Day AR. Aquatic physical therapy for hip and knee osteoarthritis: results of a single-blind randomized controlled trial. Phys Ther 2007;87:32-43.
27. Poyhonen T, Sipila S, Keskinen KL, Hautala A, Savolainen J, Malkia E. Effects of aquatic resistance training on neuromuscular performance in healthy women. Med Sci Sports Exerc 2002;34:2103-9.
28. Takeshima N, Rogers ME, Watanabe E, et al. Water-based exercise improves health-related aspects of fitness in older women. Med Sci Sports Exerc 2002;34:544-51.
29. Rahmann AE, Brauer SG, Nitz JC. A specific inpatient aquatic physiotherapy program improves strength after total hip or knee replacement surgery: a randomized controlled trial. Arch Phys Med Rehabil 2009;90:745-55.
30. Harmer AR, Naylor JM, Crosbie J, Russell T. Land-based versus water-based rehabilitation following total knee replacement: a randomized, single-blind trial. Arthritis Rheum 2009;61:184-91.
31. Rantanen T, Avela J. Leg extension power and walking speed in very old people living independently. J Gerontol A Biol Sci Med Sci 1997;52:M225-31.
32. Portegijs E, Sipila S, Rantanen T, Lamb SE. Leg extension power deficit and mobility limitation in women recovering from hip fracture. Am J Phys Med Rehabil 2008;87:363-70.
33. Gur H, Cakin N. Muscle mass, isokinetic torque, and functional capacity in women with osteoarthritis of the knee. Arch Phys Med Rehabil 2003;84:1534-41.
34. Bellamy N, Buchanan WW, Goldsmith CH, Campbell J, Stitt LW. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. J Rheumatol 1988;15:1833-40.
35. Moffet H, Collet JP, Shapiro SH, Paradis G, Marquis F, Roy L. Effectiveness of intensive rehabilitation on functional ability and quality of life after first total knee arthroplasty: a single-blind randomized controlled trial. Arch Phys Med Rehabil 2004;85:546-56.
36. Sipila S, Suominen H. Effects of strength and endurance training on thigh and leg muscle mass and composition in elderly women. J Appl Physiol 1995;78:334-40.
37. Borg G. Borg's perceived exertion and pain scales. Champaign: Human Kinetics; 1998. p 120.
38. Poyhonen T, Keskinen KL, Kyrolainen H, Hautala A, Savolainen J, Malkia E. Neuromuscular function during therapeutic knee exercise under water and on dry land. Arch Phys Med Rehabil 2001;82:1446-52.
39. Wang TJ, Belza B, Thompson EF, Whitney JD, Bennett K. Effects of aquatic exercise on flexibility, strength and aerobic fitness in adults with osteoarthritis of the hip or knee. J Adv Nurs 2007;57:141-52.
40. Lund H, Weile U, Christensen R, et al. A randomized controlled trial of aquatic and land-based exercise in patients with knee osteoarthritis. J Rehabil Med 2008;40:137-44.
41. Sipila S, Multanen J, Kallinen M, Era P, Suominen H. Effects of strength and endurance training on isometric muscle strength and walking speed in elderly women. Acta Physiol Scand 1996;156:457-64.
42. Sipila S, Elorinne M, Alen M, Suominen H, Kovanen V. Effects of strength and endurance training on muscle fibre characteristics in elderly women. Clin Physiol 1997;17:459-74.
43. Petrella JK, Kim JS, Tuggle SC, Bamman MM. Contributions of force and velocity to improved power with progressive resistance training in young and older adults. Eur J Appl Physiol 2007;99:343-51.
44. Parry-Billings M, Newsholme EA, Young A. The uptake, storage, and release of metabolities by muscle. In: Evans JG, Williams TF, editors. Oxford textbook of geriatric medicine. Oxford: University Press; 1992. p 604-8.
45. Escobar A, Quintana JM, Bilbao A, et al. Effect of patient characteristics on reported outcomes after total knee replacement. Rheumatology (Oxford) 2007;46:112-9.
46. Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KD. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? Clin Orthop Relat Res 2010;468:57-63.

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IV

MAINTENANCE OF AQUATIC TRAINING-INDUCED BENEFITS IN MOBILITY AND LOWER EXTREMITY MUSCLES AMONG PERSONS WITH UNILATERAL KNEE REPLACEMENT

by

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ORIGINAL ARTICLE

Maintenance of Aquatic Training-Induced Benefits on Mobility and Lower-Extremity Muscles Among Persons With Unilateral Knee Replacement

Anu Valtonen, MSc, Tapani Pöyhönen, PhD, Sarianna Sipilä, PhD, Ari Heinonen, PhD

ABSTRACT. Valtonen A, Pöyhönen T, Sipilä S, Heinonen A. Maintenance of aquatic training-induced benefits on mobility and lower-extremity muscles among persons with unilateral knee replacement. Arch Phys Med Rehabil 2011;92:1944-50.

Objective: To evaluate the maintenance of observed aquatic training-induced benefits at 12-month follow-up.

Design: Twelve-month follow-up of a randomized controlled study.

Setting: Research laboratory and hospital rehabilitation pool.

Participants: Population-based sample of 55 to 75-year-old women and men 4 to 18 months (on average 10mo) after unilateral knee replacement. Fifty people were willing to participate in the exercise trial and 42 people in the follow-up study.

Intervention: Twelve-month follow-up of 12-week progressive aquatic resistance training, or no intervention.

Main Outcome Measures: Isokinetic knee extensor and flexor power, thigh muscle cross-sectional area (CSA), habitual walking speed, stair ascending time, and sit-to-stand test.

Results: After a 12-month follow-up, a 32% (95% confidence interval [CI], 10–53) training effect in knee extensor power ($P=.008$) and 50% (95% CI, 9–90) in knee flexor power ($P=.005$) of the operated knee remained. In muscle CSA, the training-induced benefit had disappeared at the follow-up. All the significant 12-week improvements in habitual walking speed, stair ascending time, and sit-to-stand in the training group compared with controls were lost at follow-up.

Conclusions: After the 12-month follow-up, the 12-week aquatic training-induced benefits in knee extensor and flexor power were maintained, whereas the mobility benefits had disappeared. Aquatic resistance training should be continued at least on some level to maintain the training-induced benefits in mobility.

Key Words: Follow-up studies; Rehabilitation; Walking; Water.

KNEE JOINT OSTEOARTHRITIS and related knee replacement surgery cause muscle strength and functional decline,[1-3] which have been reported to remain lower than in age-matched people beyond 1 year and even at 13 years after surgery.[1,4-8] In our previous 12-week randomized controlled trial,[9] we showed that progressive aquatic resistance training initiated on average 10 months after knee replacement had positive effects on muscle power, muscle mass, and mobility in the lower limbs, that is, decreased functional decline in persons with knee replacement.

To date, very little is known about the maintenance of training/therapeutic exercise-induced benefits in persons with knee replacement. As far as we know, only 1 earlier study has reported maintenance of dry-land strength training in persons with knee replacement. These results showed that improvements in muscle strength and mobility observed after 6-week progressive strengthening intervention were maintained after 12-months follow-up.[10] After progressive aquatic resistance training in persons with knee replacement, the long-term effects of training are unclear. So far, the maintenance of aquatic exercise effects after knee replacement surgery has been investigated only with 2- to 6-week-long rehabilitation programs.[11,12] However, it remains somewhat unclear whether the training-induced benefits of the progressive and intensive training program with additional resistance in persons with knee replacement can be maintained after cessation of training.

The purpose of this study was to evaluate whether the observed aquatic training-induced benefits in lower-leg muscle power, cross-sectional area (CSA), and mobility,[9] assessed by habitual walking speed, stair ascending time, and the sit-to-stand test, were maintained after follow-up for 12-months in persons with knee replacement. Our hypothesis was that aquatic training-induced benefits would be maintained during the follow-up.

METHODS

Design

This study was a 12-month follow-up of a 12-week randomized, controlled aquatic resistance training intervention (register no. ISRCTN50731915). The intervention refers to a 12-week randomized controlled trial[9] and the follow-up to the 12-month period after the end of the intervention. The measurements were conducted at baseline, after the 12-week inter-

List of Abbreviations

CI	confidence interval
CSA	cross-sectional area
CT	computed tomography
ICC	intraclass correlation coefficient
WOMAC	Western Ontario and McMaster University Osteoarthritis Index

From the Department of Health Sciences, University of Jyväskylä, Jyväskylä (Valtonen, Heinonen); Rehabilitation and Pain Unit, Kymenlaakso Central Hospital, Kotka (Valtonen, Pöyhönen); and Gerontology Research Centre, University of Jyväskylä, Jyväskylä (Sipilä), Finland.

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Reprint requests to Anu Valtonen, MSc, Dept of Health Sciences, University of Jyväskylä, PO Box 35, FI-40014 University of Jyväskylä, Finland, e-mail: *anu.m.valtonen@jyu.fi*.

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Table 1: Baseline Physical Characteristics of the Participants at Follow-Up*

Characteristics	Aquatic Training Group (n=25)	Control Group (n=17)
Age (y)	65.8±6.2	66.4±5.7
Body weight (kg)	84.1±14.8	82.3±14.8
Body height (cm)	167.9±9.0	169.5±7.3
Time since operation (mo)	10.1±4.7	8.5±3.9
Comorbidities*, n (%)		
Cardiovascular	15 (60)	7 (41)
Endocrine	1 (4)	2 (12)
Musculoskeletal	12 (48)	4 (24)
Respiratory	1 (4)	1 (6)
Diagnosed knee osteoarthritis of the nonoperated knee, n (%)	3 (12)	2 (12)

NOTE. Values are the mean ± SD unless indicated otherwise. No between-group differences at baseline.
*Self-reported number of comorbidities.

vention, and at 12-month follow-up by the same research personnel. Quantitative computed tomography (CT) measurements and analyses were conducted blinded to the study group. The other measurements were conducted unblinded. This follow-up study assesses the physical performance traits that showed a treatment effect during the intervention. In addition, using the Western Ontario and McMaster University Osteoarthritis Index (WOMAC) questionnaire self-reported physical functional difficulty, pain, and stiffness are used to describe the status of the knee on the operated side during the follow-up.

Participants

In 2005, all the 201 patients who, according to the physical therapy records of Kymenlaakso Central Hospital, had undergone unilateral knee replacement 4 to 18 months prior to the study were informed about the study. Eighty-six patients were contacted by the research personnel and interviewed over the telephone. Exclusion criteria were: bilateral knee arthroplasty, revision arthroplasty, severe cardiovascular diseases, dementia, rheumatoid arthritis, and any major operation in either of the knees. Thus, 50 eligible volunteers (age range, 55–75y; 30 women and 20 men) were randomized after the baseline measurements into an aquatic resistance training group (16 women, 10 men) and a control group (14 women, 10 men). The random allocation was concealed in sealed envelopes, in blocks of sex, age, and type of knee replacement (table 1). Forty-six participants (92%) completed the training intervention.[9] During the 12-month follow-up, 4 participants in the control group dropped out. Thus, 42 volunteers completed the 12-month postintervention follow-up study (fig 1).

The reason for the participants' knee replacement surgery was knee joint osteoarthritis. Characteristics of the knee replacement operation were collected from the hospital medical records. All the participants had undergone knee replacement surgery with cement fixation (41 with tricompartmental total knee arthroplasty, 1 with unicompartmental hemiarthroplasty). Independent samples *t* test was used to verify that the person with hemiarthroplasty did not differ from the participants with total knee replacement in the baseline measurements in any of the variables.

Before the laboratory examinations, the participants were informed about the study and they gave their written informed consent. The study was conducted according to the Declaration

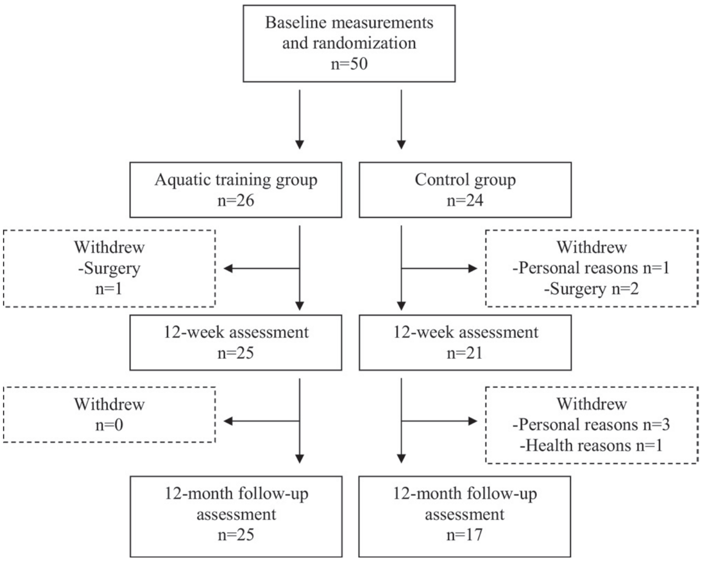

Fig 1. Trial profile.

of Helsinki and approved by the ethical committee of Kymenlaakso Central Hospital.

Intervention

The training program has been reported in the original intervention paper.[9] Briefly, the 12-week aquatic exercise was specifically targeted at improving lower-extremity muscle strength and power. Exercise sessions were conducted twice a week in small classes containing 4 to 5 persons. All the classes were supervised by an experienced physiotherapist.

Each training session consisted of 5 exercises for both legs: (1) 1-leg knee extension-flexion movement in a sitting position, (2) hip abduction-adduction with extended knee in a standing position, (3) hip extension-flexion with extended knee in a standing position, (4) 1-leg knee extension-flexion in a standing position, and (5) step-squat backwards from the aqua aerobic step board. The subjects were instructed to perform each repetition with maximal effort in order to achieve the highest possible movement velocity and resistance. The progression of the exercise program was ensured by using resistance boots of different sizes (small, medium, large) and by varying the amount and duration of sets. In the hydro-boot conditions, the movement velocities were slower and the number of repetitions per set was lower but the resistance higher compared with the barefoot condition.[13,14] The control group did not receive any intervention. Participants were encouraged to continue their lives as usual and maintain their habitual level of physical activity during the trial.

Health Status

Body height and weight were measured using standard procedures. General health, clinical history, medication, and diseases of the participants were assessed by a physician before the laboratory examinations to evaluate potential contraindications for safe participation in the measurements and training. The presence of self-reported chronic conditions was recorded with a questionnaire. In addition, the participants reported their general health and habitual physical activity at baseline, after the intervention, and at follow-up.

Knee Extensor and Flexor Power

Maximal muscle power (W) of the knee extensors and flexors in the operated leg was measured with an isokinetic dynamometer.[14 a] After a few submaximal flexion-extension movements, 5 maximal continuous flexion-extension trials were performed at an angular velocity of 180°/s. The participants were verbally encouraged to maximal effort throughout the whole range of motion. Peak power (P) values were analysed from the best extension and flexion efforts. The intraclass correlation coefficient (ICC) of the isokinetic parameters for persons with knee replacement varied between .90 and .96 for the operated knee.[3]

Muscle CSA

CT scans were obtained from mid-thigh using a Siemens Somatom DR Scanner[b] with the patient in a supine position.[15] The scans were analyzed to measure thigh muscle CSA (cm^2) using software developed for that purpose at the University of Jyväskylä (Geanie 2.1[c]). In our previous study, the coefficient of variation was calculated between 2 consecutive repeated measurements, and was 1% to 2% for muscle CSA.[15]

Mobility

Mobility was assessed by habitual walking speed, stair ascending time, and the sit-to-stand test. In all the mobility variables, each participant performed 2 trials separated by a 1-minute rest, and the faster performance was accepted as the result.

Habitual walking speed. Habitual walking speed over 10m was measured in the hospital corridor and the time taken was recorded using photocells.[16 d] All the participants were allowed 3m for acceleration.

Stair ascending. Maximal time taken to ascend 10 stairs was measured in the hospital corridor[17] and the time taken was recorded using photocells. The participants were instructed to step alternately on each stair as fast as possible without compromising their safety. A handrail or taking a step with both feet on the same step was allowed only if necessary. The ICC for ascending stairs for persons with knee replacement has been .73.[3]

Sit-to-stand. Maximal time taken to stand up and sit down 10 times on a standard chair was measured,[17] and the time taken was recorded using a stopwatch. The chair height was 43cm and the depth was 37cm. The participants were instructed to stand up and sit down as fast as possible without using their hands. The ICC for sit-to-stand was measured in our laboratory in a pilot study for 17 participants (12 women, 5 men; mean age, 77y) with unilateral knee replacement an average of 8 months after surgery. The ICC for sit-to-stand was .83 in persons with knee replacement.

Pain, Stiffness, and Physical Functional Difficulty

The WOMAC questionnaire, a self-rated measure of pain and stiffness and physical functional difficulty, is widely used after joint replacement surgery research.[12,18] The version based on the visual analog scale (range, 0–100mm, with 100 indicating the worst possible situation) was used. In the physical functional difficulty score, 80% of the participants did not answer the subscale "getting in and out of the bath" because they did not have a bath. Therefore, this subscale was not included in the analysis.

Statistical Analysis

Means and SDs were used as descriptive statistics. The data obtained from men and women were pooled to obtain a larger sample size as there were no differences between the sexes in age, time since operation, or training response. All the available participants were measured and analyzed as randomized regardless of training compliance. The outcomes for the participants who dropped out during the follow-up were not used because of our long follow-up time. Independent samples *t* test was used to verify that the dropouts did not differ from the other participants in any characteristics or outcome variables. Participants with missing values in the physical performance tests (2 because of acute knee surgery, 3 because of other health problem) or in the CT measurement (2 because of unwillingness to participate) were omitted only from the analysis in question.

SPSS 17.0[e] was used for statistical analysis. All the variables were normally distributed. The analysis of covariance was used to assess the training effect at posttrial and follow-up training measurements between the training and control groups. Age, sex, time since operation, and training compliance were tested separately and together as covariates. Because they had no influence on the results, only the baseline measurement was used as covariate.

The relative change in muscle power, muscle CSA, and mobility between the pre- and posttrial measurements as well as pretrial and follow-up measurements was calculated as (post – pre)/pre × 100% or (followup – pre)/pre × 100%. The

Table 2: Mean ± SD Values at Baseline, at the End of the Intervention, and at Follow-Up in the Aquatic Training and Control Groups

Variable	Aquatic Training Group				Control Group			
	n	Baseline*	Posttrial	Follow-Up	n	Baseline*	Posttrial	Follow-Up
KEP (W)	21	112.6±51.4	145.6±64.0	144.6±60.5	16	133.2±45.4	130.8±41.4	134.7±53.7
KFP (W)	21	99.8±49.4	135.9±60.0	137.1±63.2	16	118.3±43.6	119.4±40.0	122.5±52.7
Thigh muscle CSA (cm^2)	25	105.2±30.0	110.1±30.7	109.3±28.4	15	101.2±20.7	103.3±19.6	105.6±22.1
Habitual walking speed (m/s)	21	1.31±0.18	1.41±0.24	1.39±0.15	16	1.33±0.23	1.34±0.23	1.35±0.24
Stair ascending (s)	21	4.96±2.10	4.27±1.67	4.39±1.54	16	4.86±1.96	4.77±1.82	4.77±1.90
Sit-to-stand 10 repetitions (s)	21	21.4±3.42	17.8±1.94	19.0±3.18	16	21.8±4.01	20.4±3.46	19.4±4.6
WOMAC total score† (mm)	25	22.4±10.6	17.9±8.5	17.4±10.3	17	16.7±12.5	17.7±17.8	14.6±10.1
Pain score‡ (mm)	25	16.8±10.6	13.0±8.7	13.3±8.9	17	15.7±15.1	15.3±13.2	9.5±6.8
Stiffness score‡ (mm)	25	32.7±24.0	25.9±20.6	21.7±14.8	17	23.3±17.9	27.0±24.8	22.1±20.7
Physical functional difficulty score‡ (mm)	25	22.6±11.7	18.5±9.4	18.1±11.0	17	15.9±12.5	16.9±19.1	14.8±11.0

Abbreviations: KEP, knee extensor power; KFP, knee flexor power; Thigh muscle CSA, thigh lean tissue cross-sectional area.
*No between-group differences in any of the variables at baseline.
†Total score of WOMAC questionnaire based on the visual analog scale.
‡Assessed with WOMAC questionnaire, subscales of pain, stiffness, and physical functional difficulty based on the visual analog scale.

differences (effect) in the mean relative changes between the study groups and the 95% confidence intervals (CIs) of the difference were also calculated.

RESULTS

Participation in the Follow-Up

Forty-two participants (84%) were measured in the follow-up assessment. All the participants from the training group participated in the follow-up assessment session, whereas 4 subjects in the control group withdrew from the study during the follow-up period (see fig 1). During the 12-month follow-up, 2 participants in the training and 1 in the control group also had their nonoperated knee replaced. One participant in each group had revision arthroplasty during the follow-up. At the follow-up measurements, 2 participants in the training group (asthma, sprain in the ankle) and 1 in the control group (sprain in the knee) had acute health problems, and consequently they attended only to the CT measurements and completed the questionnaires. At follow-up, 3 participants in the training and 1 in the control group had increased their habitual physical activity, and 2 participants in the training and 3 in the control group had decreased their habitual physical activity. None of the participants continued aquatic resistance training after the intervention.

Muscle Power and CSA

The absolute values at baseline, at the end of the intervention, and at the 12-month follow-up are presented in table 2. After the 12-week intervention, significant ($P<.037$) training effects of 3% to 49% were observed in knee extensor and flexor power and in thigh muscle CSA in the training group compared with controls (tables 2 and 3). At 12-month follow-up, a 32% (95% CI, 10–53) effect in knee extensor power and 50% (95% CI, 9–90) effect in knee flexor power of the operated knee remained in the training group compared with the control group (fig 2). In thigh muscle CSA, the training-induced benefit had disappeared at follow-up.

Mobility

After the intervention, significant ($P<.025$) training effects of 7% to 12% were observed in habitual walking speed, stair ascending time, and sit-to-stand in the training group compared with controls (see tables 2 and 3). However, at follow-up, no between-group differences were seen in any of the mobility variables (fig 3).

Pain, Stiffness, and Physical Functional Difficulty

The scores for physical functional difficulty, pain, and stiffness in the operated knee were not affected by training ($P<.310$). At follow-up, no between-group differences

Table 3: 12-Week Training Effect (95% CI) and 12-Month Follow-Up Mean Difference (95% CI)

Variable	Training Effect %* (95% CI)	ANCOVA $P^†$	Mean Difference % at Follow-Up* (95% CI)	ANCOVA $P^†$
KEP (W)	33 (17 to 50)	<.001	32 (10 to 53)	.008
KFP (W)	49 (3 to 94)	.008	50 (9 to 90)	.005
Thigh muscle CSA (cm^2)	3 (0 to 5)	.037	−1 (−5 to 3)	.486
Habitual walking speed (m/s)	7 (1 to 14)	.025	2 (−6 to 11)	.414
Stair ascending (s)	−12 (−21 to −4)	.015	−8 (−19 to 4)	.229
Sit-to-stand 10 repetitions (s)	−10 (−16 to −4)	<.001	0 (−11 to 12)	.995

Abbreviations: ANCOVA, analysis of covariance; KEP, knee extensor power; KFP, knee flexor power; Thigh muscle CSA, thigh lean tissue cross-sectional area.
*12-week training effect percent and 12-month follow-up mean difference calculated as the relative mean difference (95% CI) between the study groups.
†Derived from the ANCOVA using the absolute values at the end of the intervention and at follow-up; baseline as the covariate.

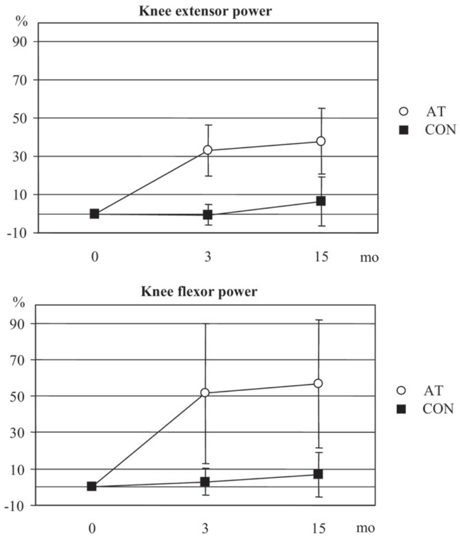

Fig 2. Muscle power variables for the aquatic training and control groups: knee extensor power, knee flexor power. Percentage change (95% CIs) for the training and control groups after the intervention (3mo) and at 12-month follow-up (15mo=12mo after cessation of training). Abbreviations: AT, aquatic training group; CON, control group.

($P<.896$) were observed in the physical functional difficulty score, pain, or stiffness (see table 2).

DISCUSSION

In this 12-month follow-up of a 12-week randomized controlled aquatic training intervention after knee replacement surgery, training-induced benefits in the knee extensor and flexor power remained q year after cessation of training. However, the training effects in mobility and muscle CSA had disappeared. The present results support our hypothesis, showing that in the training group in persons with knee replacements, knee extensor and flexor power was maintained at the posttraining level 12 months after cessation of training. Previously, from 8 to 12 weeks of aquatic training in different clinical populations have shown maintained[19] or decreased[20] lower-limb strength levels 3 months after cessation of training. In addition, Petterson et al[10] found that 2 different dry-land training groups with knee replacements were stronger than a nontraining cohort 12 months after cessation of training. However, these earlier inconsistent results cannot directly be compared with our results because of differences in the clinical populations,[19,20] training programs, environments and resistances used in the training protocols,[10,19,20] or our longer follow-up period.[10,19,20]

In contrast, the training effect on muscle CSA had disappeared at the follow-up. To our knowledge, no earlier studies in persons with knee replacement have reported on the maintenance of muscle CSA after strength training. In healthy older adults, muscle CSA was maintained[21] or decreased[22] during a 6-month detraining period. In the present study, thigh muscle CSA in the training group was maintained at the posttraining level, but the between-group difference disappeared because of the slight increase in muscle CSA in the controls. It seems that 12 months without physical training was too long a period to maintain training effects on muscle CSA. Nevertheless, the habitual physical activity of the participants was sufficient to enable them to maintain the training-induced muscle power.

In this study, the training effect on mobility in our study disappeared after the 12-month follow-up period. This is contrary to our hypothesis and to previous studies which have found further improvements in mobility from 3 to 12 months after cessation of training in persons with knee replacement,[10,11] However, previous studies and our study are not fully comparable, as the interventions in the former studies

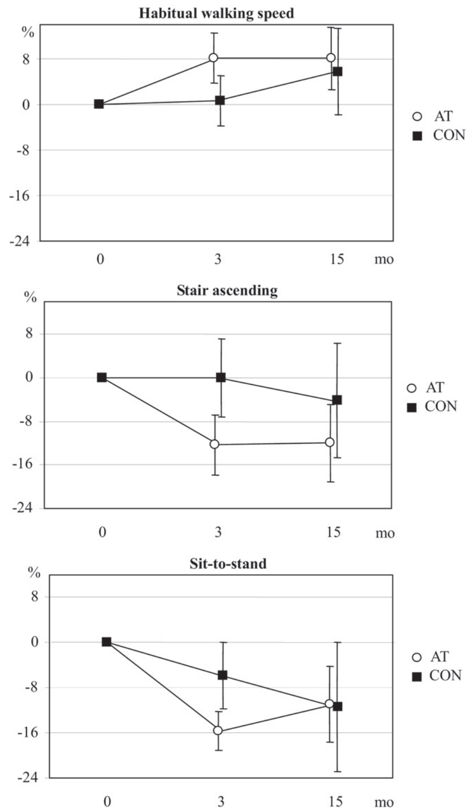

Fig 3. Mobility variables for the aquatic training and control groups: habitual walking speed, stair ascending, sit-to-stand. Percentage change (95% CIs) for the training and control groups after the intervention (3mo) and at 12-month follow-up (15mo=12mo after cessation of training). Abbreviations: AT, aquatic training group; CON, control group.

commenced in the acute recovery phase (<4wk) after surgery which was not the case in our study. In addition, a control group was not included in 1 study[11] or the training was conducted on dry land.[10] On the other hand, our findings are in line with the studies in persons with fibromyalgia, where the muscle strength was maintained after the detraining period but mobility was not.[19,23] We believe that these results may indicate that the mobility demands of daily living or the participants' habitual physical activity were not enough to maintain the training-induced changes in mobility. Indirectly, these results highlight that knee replacement patients should start rehabilitation immediately after surgery and as a regular part of the rehabilitation process to be encouraged to be physically active, because a sedentary life style increases the risk for health problems, which in turn reduces a person's functional ability. During our follow-up period, 3 persons had acute health problems and were not able to participate in the physical performance measurements. In addition, 3 participants had their nonoperated knee diagnosed and replaced during the follow-up period, which is common after knee replacement surgery.[24,25] This might also have influenced the maintenance of benefits in mobility.

Because it is challenging to persist in intensive supervised training endlessly to prevent mobility problems, periodical intensive training, as suggested by Karinkanta et al,[26] or physical activity counseling[27] would perhaps help people to maintain a good level of habitual physical activity. Aquatic training offers a suitable training environment for periods of intensive training. Water is a safe and effective environment. It reduces the compressive forces on joints while at the same time offers resistance to movements. Therefore, in water, it is possible to perform each repetition with maximal effort in a pain-free mode and achieve the highest possible movement velocity and thus resistance. In addition, a pain-free aquatic training environment may also encourage patients to move with high movement velocity in everyday life and thus maintain the training-induced benefits in muscle power.

Study Limitations

Our study had some limitations. Not all the participants attended the follow-up measurements, although compliance (84%) was nevertheless quite high. Unfortunately, we had only 1 follow-up measurement, which was conducted 12 months after cessation of training. For example, a follow-up measurement after 3 months would also have offered interesting data about maintenance of mobility. We performed multiple comparisons on this data, and it is possible that a study-wide type I error exists. We were not able to conduct complete blinding, which limits the strength of the conclusions. Finally, we were not able to do any subanalysis, whereby participants with confounding factors would be excluded, because of the small number of participants in this study.

This study has several strengths. First, this follow-up study evaluated the maintenance of the treatment effects of a randomized controlled trial after knee replacement surgery with only a few dropouts during the follow-up period. Second, the recruitment of the participants was population-based and the study group was homogeneous. Third, the maintenance of aquatic resistance training-induced benefits in persons with knee replacement was compared with that of a control group.

CONCLUSIONS

Aquatic resistance training-induced benefits in knee extensor and flexor power were maintained at 12-month follow-up in persons with knee replacement. However, 12 months seemed to be too long a period for the gains achieved in mobility to be maintained by regular physical activity alone.

References

1. Walsh M, Woodhouse LJ, Thomas SG, Finch E. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. Phys Ther 1998;78:248-58.
2. Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. J Orthop Sports Phys Ther 2005;35:424-36.
3. Valtonen A, Poyhonen T, Heinonen A, Sipila S. Muscle deficits persist after unilateral knee replacement and have implications for rehabilitation. Phys Ther 2009;89:1072-9.
4. Huang CH, Cheng CK, Lee YT, Lee KS. Muscle strength after successful total knee replacement: a 6- to 13-year followup. Clin Orthop Relat Res 1996;(328):147-54.
5. Berth A, Urbach D, Awiszus F. Improvement of voluntary quadriceps muscle activation after total knee arthroplasty. Arch Phys Med Rehabil 2002;83:1432-6.
6. Silva M, Shepherd EF, Jackson WO, Pratt JA, McClung CD, Schmalzried TP. Knee strength after total knee arthroplasty. J Arthroplasty 2003;18:605-11.
7. Meier W, Mizner RL, Marcus RL, Dibble LE, Peters C, Lastayo PC. Total knee arthroplasty: Muscle impairments, functional limitations, and recommended rehabilitation approaches. J Orthop Sports Phys Ther 2008;38:246-56.
8. Yoshida Y, Mizner RL, Ramsey DK, Snyder-Mackler L. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. Clin Biomech (Bristol, Avon) 2008;23:320-8.
9. Valtonen A, Poyhonen T, Sipila S, Heinonen A. Effects of aquatic resistance training on mobility limitation and lower-limb impairments after knee replacement. Arch Phys Med Rehabil 2010;91:833-9.
10. Petterson SC, Mizner RL, Stevens JE, et al. Improved function from progressive strengthening interventions after total knee arthroplasty: a randomized clinical trial with an imbedded prospective cohort. Arthritis Rheum 2009;61:174-83.
11. Harmer AR, Naylor JM, Crosbie J, Russell T. Land-based versus water-based rehabilitation following total knee replacement: a randomized, single-blind trial. Arthritis Rheum 2009;61:184-91.
12. Rahmann AE, Brauer SG, Nitz JC. A specific inpatient aquatic physiotherapy program improves strength after total hip or knee replacement surgery: a randomized controlled trial. Arch Phys Med Rehabil 2009;90:745-55.
13. Poyhonen T, Keskinen KL, Kyrolainen H, Hautala A, Savolainen J, Malkia E. Neuromuscular function during therapeutic knee exercise under water and on dry land. Arch Phys Med Rehabil 2001;82:1446-52.
14. Poyhonen T, Sipila S, Keskinen KL, Hautala A, Savolainen J, Malkia E. Effects of aquatic resistance training on neuromuscular performance in healthy women. Med Sci Sports Exerc 2002;34:2103-9.
15. Sipila S, Suominen H. Effects of strength and endurance training on thigh and leg muscle mass and composition in elderly women. J Appl Physiol 1995;78:334-40.
16. Portegijs E, Sipila S, Rantanen T, Lamb SE. Leg extension power deficit and mobility limitation in women recovering from hip fracture. Am J Phys Med Rehabil 2008;87:363-70.
17. Gur H, Cakin N. Muscle mass, isokinetic torque, and functional capacity in women with osteoarthritis of the knee. Arch Phys Med Rehabil 2003;84:1534-41.
18. Moffet H, Collet JP, Shapiro SH, Paradis G, Marquis F, Roy L. Effectiveness of intensive rehabilitation on functional ability and quality of life after first total knee arthroplasty: a single-blind

randomized controlled trial. Arch Phys Med Rehabil 2004;85: 546-56.
19. Gusi N, Tomas-Carus P, Hakkinen A, Hakkinen K, Ortega-Alonso A. Exercise in waist-high warm water decreases pain and improves health-related quality of life and strength in the lower extremities in women with fibromyalgia. Arthritis Rheum 2006;55:66-73.
20. Lund H, Weile U, Christensen R, et al. A randomized controlled trial of aquatic and land-based exercise in patients with knee osteoarthritis. J Rehabil Med 2008;40:137-44.
21. Ivey FM, Tracy BL, Lemmer JT, et al. Effects of strength training and detraining on muscle quality: age and gender comparisons. J Gerontol A Biol Sci Med Sci 2000;55:B152-7; discussion B158-9.
22. Taaffe DR, Henwood TR, Nalls MA, Walker DG, Lang TF, Harris TB. Alterations in muscle attenuation following detraining and retraining in resistance-trained older adults. Gerontology 2009;55:217-23.
23. Tomas-Carus P, Hakkinen A, Gusi N, Leal A, Hakkinen K, Ortega-Alonso A. Aquatic training and detraining on fitness and quality of life in fibromyalgia. Med Sci Sports Exerc 2007;39:1044-50.
24. Ritter MA, Carr KD, Keating EM, Faris PM. Long-term outcomes of contralateral knees after unilateral total knee arthroplasty for osteoarthritis. J Arthroplasty 1994;9:347-9.
25. McMahon M, Block JA. The risk of contralateral total knee arthroplasty after knee replacement for osteoarthritis. J Rheumatol 2003;30:1822-4.
26. Karinkanta S, Heinonen A, Sievanen H, Uusi-Rasi K, Fogelholm M, Kannus P. Maintenance of exercise-induced benefits in physical functioning and bone among elderly women. Osteoporos Int 2009;20:665-74.
27. Mänty M, Heinonen A, Leinonen R, et al. Long-term effect of physical activity counseling on mobility limitation among older people: a randomized controlled study. J Gerontol A Biol Sci Med Sci 2009;64:83-9.

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