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Effects of Progressive Resistance Strength Training on Knee Biomechanics During Single Leg Step-up in Persons with Mild Knee Osteoarthritis

Kevin James McQuade, PhD and
Department of Rehabilitation Medicine, Physical Therapy Program, University of Washington, Seattle, WA, USA

Anamaria Siriani de Oliveira, PhD
Department of Biomechanics, Medicine and Rehabilitation of Locomotor Apparatus, Physical Therapy Program, University of São Paulo, Ribeirão Preto, SP, Brazil

Abstract

Background—The goal of this study was to determine if increasing strength in primary knee extensors and flexors would directly affect net knee joint moments during a common functional task in persons with knee osteoarthritis.

Methods—An exploratory single sample clinical trial with pre-post treatment measures was used to study volunteers with clinical diagnosis of mild knee OA in one knee. Subjects participated in an individually supervised training program 3 times a week for eight weeks consisting of progressive resistive exercises for knee extensors and knee flexors. Pre and post training outcome assessments included: 1. Net internal knee joint moments, 2. Electromyography of primary knee extensors and flexors, and 3. Self-report measures of knee pain and function. The distribution of lower extremity joint moments as a percent of the total support moment was also investigated.

Findings—Pain, symptoms, activities of daily life, quality of life, stiffness, and function scores showed significant improvement following strength training. Knee internal valgus and hip internal rotation moments showed increasing but non-statistically significant changes post-training. There were no significant differences in muscle co-contraction activation of the Quadriceps and Hamstrings.

Interpretations—While exercise continues to be an important element of OA management, the results of this study suggest improvements in function, pain, and other symptoms, as a result of strength training may not be causally related to specific biomechanical changes in net joint moments.

Keywords

Biomechanics; Exercise; Osteoarthritis; Knee; Rehabilitation

Corresponding Author: Kevin James McQuade [kmcquade@u.washington.edu] Mail to: 1959 NE Pacific Street, Suite CC-902S, Seattle, Washington –USA, 98195-6490. Phone: +1 206 598-5411 Fax: +1 206 685-3244.

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INTRODUCTION

Treatments for knee osteoarthritis (OA) attempt to decrease pain and stiffness, and increase function through a variety of approaches. These approaches include pharmacological, surgical, physical therapy modalities, orthotics and braces, and exercise. Exercises specifically aimed at muscle strengthening have been used as the cornerstone of most exercise rehabilitation programs (Myers 1995), and the American College of Rheumatology (ACR) recommends strengthening exercise for the management of knee OA symptoms (Hochberg, Altman et al. 1995).

Strength training is presumed to protect the joint from pathologic stress and loading. Programs to strengthen knee extension and flexion have resulted in significant strength gains and appear to reduce pain and improve function (Messier, Loeser et al. 1992; Marks 1993; Fisher, White et al. 1997; Rogind, Bibow-Nielsen et al. 1998; Maurer, Stern et al. 1999; Minor 1999; Baker and McAlindon 2000; Roddy, Zhang et al. 2005). The beneficial effects of resistive exercise for individuals with OA may be attributed to several associated factors such as: facilitation of endogenous opiates which creates an analgesic effect to improve a person's tolerance to pain (Fraioli, Moretti et al. 1980; Carr, Bullen et al. 1981; Allen 1983), decrease in depression coupled with perceived level of disability (Minor and N.E. 1996; van Baar, Dekker et al. 1998), through associated weight loss (Jenkinson, Doherty et al. 2009), or mechanically through alteration of the biomechanics of the joint (Thorstensson, Henriksson et al. 2007). It is this latter point that this study is designed to address by investigating joint moment changes associated with a strength training intervention. While there may be physiological and psychological effects related to strengthening, it is the mechanical effects that might have the most direct influence on the knee joint itself. Since abnormal or excessive joint loading can lead to articular cartilage degradation (Pearle, Warren et al. 2005), it is clinically assumed that the positive influence of strengthening the knee musculature on OA symptoms and other knee joint problems, is due to the strengthened muscle's ability to "stabilize" or "reduce stress" in the knee joint. In a review by Bennell et al, the author's stated "… *Improving the load-bearing capacities of lower-limb muscles—in particular, the quadriceps—through strength-training and muscle rehabilitation programs may protect against soft tissue damage resulting from excessive load*"(Bennell, Hunt et al. 2009). This commonly held belief has had limited studies looking at specific causal relationships between strength and actual internal knee moment adaptations. Thorestensson et al. tested an 8 week training program for effects on knee adduction moment in early knee OA patients (Thorstensson, Henriksson et al. 2007). Although they reported a statistically significant reduction in external knee adduction moment following the training, the actual reduction was less than 1 Nm, which may not be clinically significant. In addition, the intervention program included motor control oriented training, education in alignment, and stretching exercises. Educating persons on proper technique and motor control can affect alignment (Kato, Urabe et al. 2008), and may have accounted for the observed small change in the joint moment. Mikesky et al. looked at whether muscle strength appeared to be related to OA progression (Mikesky, Mazzuca et al. 2006). In patients with established OA at baseline, the joint space narrowing was not significantly different at 30 months in the strength-trained group compared to the non-strength group. In addition, the frequency of incident loss of joint space beyond their measurement error was not different between the groups. There were also similar osteophyte scores between the groups. In a cohort of 1269 women and 1006 men aged 50–79 years-old with, or at risk for, knee OA, Segal et al reported that neither concentric quadriceps strength, nor Hamstring/Quadricep ratios predicted the development of knee symptoms during a 15- & 30-month longitudinal study.(Segal, Torner et al. 2009)

In their extensive review Bennel et all (Bennell, Hunt et al. 2009) posed the question: *"Do improvements in muscle function lead to improved symptoms and joint structure in knee OA?* While there is ample evidence that strengthening helps patients with OA, they concluded, *"…definitive conclusions regarding the mechanistic effects of strengthening cannot be drawn…"*

Sharma's group has made significant contributions to our understanding of risk factors with knee OA. Their group has shown that varus/valgus malalignment is a significant risk factor for the progression of OA and that persons with greater knee extensor strength are actually associated with increased progression on Knee OA, at least in patients with malaligned or lax knees. (Sharma, Song et al. 2001). They concluded greater strength has not been shown to make significant changes in the course of degenerative joint disease of the knee. (Sharma 2003) and suggested that approaches beyond strengthening exercises should be developed to enhance joint-protective muscle activity.(Sharma, Dunlop et al. 2003). However these results may pertain to only to persons with significant malalignment where greater strength may be associated with greater overall activity levels in these persons and result in increased abnormal knee joint loads due to the malalgnment thus facilitating the progression of their OA. In other populations such as patients post menisectomy, normalizing lower limb muscle strength has been associated with improved joint biomechanics such as lowering frontal plane knee moments (Sturnieks, Besier et al. 2008)

In a large Framingham subset study 1,279 people had knee x-rays and activity evaluation and were followed for nine years. Those exercising even at vigorous intensities had no greater risk of developing OA than participants who did not exercise (Felson, Niu et al. 2007), and the arthritis foundation continues to recommend exercise and in particular strengthening exercises for patients with OA in any joint. (see http://www.arthritis.org/types-exercise.php.)Therefore, the objective of this study was to investigate the biomechanical response to strengthening primary knee joint musculature that may directly influence deleterious knee joint mechanical loading. The goal was to explore whether changing strength alone in primary knee extensors and flexors would cause knee joint sagittal and frontal plane moments to be altered during a common functional task. Since stair climbing is a stressful and important locomotor functional activity, we have chosen to evaluate the knee biomechanics during stair stepping. Moreover we looked at the total support moment and proportional distribution of Hip extensor, knee extensor, and ankle extensor moments to the total support moment as an indicator of kinetic motor strategy changes. Muscle activation pattern changes for six muscles supporting the knee joint were also evaluated. Understanding the mechanisms of how this intervention affects symptoms is critical to providing, optimal care for patients with joint injury and joint disease.

METHODS

Participants

Subject inclusion criteria were: 1. Adults between 40 and 60 years of age, 2. Physician's clinical diagnosis of mild knee OA using ACR criteria(Altman, Asch et al. 1986) (The ACR criteria can be found in detail at http://www.hopkins-arthritis.org/physician-corner/education/acr). The criteria rely on physical examination, age, self-reports of pain and stiffness, and radiographic reports if available, 3. Report no higher than moderate knee pain 50% of the time in past month using a 5-point Likert scale (Bucher 1991), 4. Not participating in a regular program of physical activity at time of enrollment (defined as 30–45 minutes of moderate intensive activity 3–5 times per week) and 5. Stable on any analgesic or anti-inflammatory medications used to treat their knee OA and, if medically justifiable, agree not to alter their medications or undergo any joint injections for the duration of the trial. Potential participants were excluded if: 1. They presented radiographic evidence of misalignment greater than 5 degrees of varus or valgus angulations or severe joint space narrowing, 2. They had any knee flexion contractures, 3. They had cardiovascular, respiratory or musculoskeletal conditions other than the knee OA or any serious medical condition that precludes participation in an exercise program, 4. Were unable to walk or exercise without the use of an assistive device, or 5. Had Glucocorticoid injection to the knee joint within the past 30 days or anticipated within the next 30 days or hylauronic acid injection within the past 90 days.

Twenty-one participants were recruited from UW Medical Center and Seattle metropolitan area through fliers and word of mouth. The average age was 55.8 years (± 5.8 years), average height 1.65 m (± 0.1 m), and average mass 80.8 Kg (± 19 Kg). The sample was 76% female. The demographic data are presented in detail in Table 1. One participant failed to return for follow-up and two participants were not included in analysis due to data corruption. The drop out subject dropped for motivational reasons, the other two subject's data could not be analyzed due to technical equipment problems. All participants completed the Informed Consent Process approved by the Institution Review Board.

Outcome measures

The measures obtained in this study included: surface electromyography, knee joint biomechanics; (net joint moments, net knee internal forces) and self-report measures of knee pain and function. Maximum voluntary isometric strength as well as the ten-repetition maximum test (10RM) was used to set up the initial exercise intensity and monitor progress.

Electromyography—Surface electromyography (EMG) data were obtained using a Delsys system (DelSys Inc Boston, MA 02215.), single differential Ag/AgCl surface electrodes with a diameter of 0.8mm and inter-electrode distance of 1.0cm. The EMG signals were sampled at 1200 Hz and differentially amplified (input impedance $10^{15}\Omega$// 0.2pF, common mode rejection ratio (CMRR) 92dB @ 60 Hz, adjustable gain from 500–10,000)[b]. Electrode placement for the medial & lateral hamstrings, vastus lateralis, rectus femoris, and vastus medialis was used as described by Cram and Kasman (Cram and Kasman 1998). RMS values from three anterior thigh muscles were averaged to represent quadriceps EMG data, while the two posterior thigh muscles activity averaged represented collectively the hamstrings EMG data (Hakkinen, Kallinen et al. 1991; Babault, Pousson et al. 2002; Pereira and Goncalves 2010).

Knee Biomechanics—Six infrared cameras(Qualisys ProReflex MCU 240, Packhusgatan 6, S-411 13 Gothenburg, Sweden) were used to record position of marker clusters fixed to rigid plastic bodies attached to the pelvis, thighs, shanks, and feet of each subject bilaterally (Figure 1). Additional anatomical landmarks were digitized directly using a 3D digitizer. The digitized anatomical landmarks were used to scale segment anthropometry and to define local reference frames for each segment. The hip joint center was determined using pelvis offsets as described by Bell et.al (Bell, Pedersen et al. 1990). The knee and ankle joint centers were defined as the midpoint of medial and lateral knee joint and ankle joint markers respectively.

Two forceplates (Bertec Corporation, Columbus, OH,), one embedded in the floor and one mounted on a 20 cm high step, were used to record external stance forces and as event indicators for normalization of the step task. Net joint moments were determined using standard inverse dynamics methods (Riener and Straube 1997) utilizing the segment kinematics and ground reaction forces from the two force platforms.

Strength measures—Lower extremity quadriceps and hamstring strength was assessed using maximum voluntary isometric contraction (MVIC) effort tests with the knee flexed at an angle of 45 degrees. Based on clinical experience, 45 degrees is a position well tolerated by most patients with knee problems where then can exert maximal efforts with little or no pain. Forty-five to sixty degrees is also the range of peak torque for knee extensors. A custom-designed torque transducer was mounted to an examination table with an adjustable arm to allow for isolated knee flexion and extension testing. After familiarization, the best of three trials was used as the maximum isometric torque. The MVIC tests were also used to obtain EMG amplitudes to normalize the EMG allowing for inter-subject comparisons. To set up subjects Training loads, 10RM testing (Ferguson and Mayhew 2004) was also performed for knee extensors and knee flexors.

Knee pain and function—The Knee injury and Osteoarthritis Outcome Score (KOOS) (Roos, Roos et al. 1998) was used to provide a self-reported joint-specific measures. KOOS consists of five subscales or sub-domains: Pain, Symptoms, ADL Function, Sport and Recreation Function, and knee related Quality of Life. Standardized answer options are given (5 Likert boxes) and each question is scored from 0–4. Normalized scores (100 indicating no symptoms or best health state and 0 indicating extreme symptoms or worst health state) were calculated for each subscale.

Intervention protocol

The strengthening program was based on the well-established principles of progressive resistive exercises consistent with American college of Sports Medicine guidelines (ACSM 2009) The training program duration was 8-wks. Participants were required to complete three exercise sessions per week, each lasting a maximum of one half-hour, making 24 total sessions. Each exercise session began with a 5-minute warm-up on a stationary bicycle. Exercise sessions consisted of isotonic knee extension and flexion and leg-press exercises on weight training machines. All exercises were performed bilaterally. Participants were evaluated for ten repetitions maximum (10RM) for each exercise weekly. Exercise resistances were targeted at 60%–85% of patient’s 10RM. Participants completed three sets of 10 repetitions at each session. Using the progressive resistive loading principle, the first set was at an effort level of 60–65% 10RM, the second set at 70–75% 10RM, and the third set at 80–85% 10RM effort. There was a 2-minute rest between sets. The exercise sessions were completed within 30 minutes. A Physical Therapist directly supervised all exercise sessions.

Testing procedures

One week prior to initiating the training program, participants were assessed in the Human Motion Analysis laboratory. Participants were instrumented with motion capture markers and EMG and described above. Isometric strength values were obtained. Following a five-minute rest, participants were asked to perform five step-ups onto a 20 cm high step at a self-selected pace. They were instructed to step as smoothly as possible and not jump up. The beginning of the step was defined by initial heel contact on the ground force plate with the contralateral (uninvolved) leg and the step was completed when the subject was standing straight with both legs on the top step Subjects were asked to step up leading with one leg five times and then with the other leg five times. The order of which leg went first was randomized.

Data analysis

The tasks were temporally normalized to 100% of the step cycle based on initial contact with the ground force plate and to complete standing bilaterally on the top of the step. The average of five step-ups was used to create a representative step-up. The total support moment (TSM) was calculated as the sum of the extensor moments of the hip, knee, and ankle. Each joint contributed some percentage of the TSM and changes in the distribution of the joint moments that contributed to the TSM were considered indicators of motor pattern changes associated with the strength-training program. A negative number for percentage TSM change means that the percentage of the maximal moment coming from knee joint, for example, decreased from pre- to post-intervention.

The raw EMG was RMS processed using a 55ms time constant window and normalized to the subject's MVIC for knee flexion and extension with the knee at a 45-degree angle. EMG was evaluated by determining the total muscle activity work during stepping up (area under the RMS EMG curve during the task). Mean Hamstring/mean Quadriceps EMG ratios of total work were calculated as an index of co-contraction of thigh muscles (Pereira and Goncalves 2010).

Mean, median and standard deviations were calculated for joint moments, and normalized EMG. Normalized median and range scores were calculated from KOOS subscales as representatives of knee pain and function.

Because of the limited sample size and uncertainty associated with normality assumptions, the Wilcoxon Signed Rank Test was used to assess the pre- to post-training differences in joint kinetics and kinematics, and EMG. The data were analyzed using SPSS 17.0 and the significance level was set at alpha<0.05.

Results

Effect of training program

The intensive strength training program was tolerated well by all participants. There were no complaints of knee pain exacerbations because of the exercises. The knee extensors showed greater strength gains compared to the knee flexors. Participants' strength changes ranged from >30% for the pre-post training MVIC of the involved knee extensors to about 2% for the uninvolved knee flexors. In addition to the Pre-Post MVIC values the participants showed even greater changes in their dynamic training 10RM loads.

Self-report measures of knee pain and function – KOOS

Table 2 shows the results for the functional and psychosocial measures collected through the KOOS scores. Except for the median scores related to Sports/Recreation sub domain, all subscales of the KOOS were statistically significant. Scores in these scales were higher at the post-intervention time, reflecting an improvement in pain, symptoms, activities of daily life, quality of life, stiffness, and function.

Net internal Knee joint moments

In general, there were little changes in the net moments (P=0.05–0.65) as determined by the inverse dynamics analysis, associated with the strength-training program (Table 3). The peak loading during the step up occurred between 30–80% of the step up. During this time, tendency for greater knee internal valgus moments (Figure 2), but this did not reach a level of statistical significance (P=0.08). Hip internal rotation as well as abduction moments similarly shifted post-training to be marginally increased (P=0.05) (Figure 3).

Table 4 shows the mean distribution of net moments as a percent of the total support moment revealing very little strategic change in the way moments were distributed before and after training. There was high variability of the total support moment distribution attributable to the knee extensor, hip extensor, and ankle extensor net joint moments during step-up. Taken collectively there was a small trend for subjects to rely on more hip extension to power the step up by generating greater hip extension moments compared to knee extension moments after training. However, the strategy used to generate the total lower limb moment varied considerably from subject to subject.

Electromyography

Neither the mean nor median total Hamstrings nor Quadriceps EMG activation levels changed significantly (P=0.51–0.73) pre to post (Table 3). As an indication of co-contraction, we analyzed the H/Q ratios. There was a small trend for this ratio to increase after training suggesting some motor recruitment pattern adaptation but this was not statistically significant (P=0.59).

Discussion

The results of this study suggest that while patients self-report functional and psychosocial improvements associated with strength training, these improvements may not be causally linked to any direct biomechanical adaptations. Therefore, it questions the presumption that strength training directly effect knee joint mechanics in patients with mild OA and no significant pre-training weakness. Based on the studied sample, the peak knee extensor moments during the step-ups averaged about 25% of the participant’s maximal isometric knee extensor moment, suggesting that the step-up was a relatively low demand task. In other words, even though a patient can maximally lift more weight due to strength training, it may not change functional activities such as walking and even stair climbing if these are already a low percentage of person’s maximum strength capacity. It is possible that higher demand tasks would have shown more adaptive responses.

In a recent eight week training study with OA patients grade III or lower on the Kellegren/ Lawrence classification, Jan et al (Jan, Lin et al. 2008) reported no significant difference in any measures of pain, function, walking time, and muscle moment between groups randomly assigned to high-resistance strength exercise group, low-resistance exercise group, or no exercise. This supports the question raised in this study of how much increase in strength is enough to be considered clinically necessary. These data are currently unavailable, but warrant study to determine minimum capacities based on age, gender, and perhaps BMI, for a variety of functional activities similar to the way in which physical capacity requirements are determined for many occupational groups (Sothmann, Gebhardt et al. 2004).

In this study, we used the percent of the total support moment (TSM) (Table 4) as an indicator of the motor strategy used by individuals in distributing extensor moment across the ankle, knee and hip joints when performing a step up. Our data suggest that there is potential redistribution in that patients tended to drive more of the step up using hip extensors after training. This was unexpected because we would speculate that if the knee extensors were strengthened this would allow patients to shift their stepping strategy more toward using the knee extensors. This shift toward the hip extensors only occurred in the patient’s involved limb. It may be possible that such a strategy may unburden the knee and reduces knee OA symptoms.

Table 4 suggests that different combinations of extensor moments in the Hip, knee, and ankle, can be adopted to accomplish the step-up task. This is analogous to the description of ankle, hip, and trunk strategies that can be adopted to maintain balance (Deniskina, Levik et al. 2001). This way of looking at stepping may prove useful in the future to delineate different internal moment strategies to accomplish the same task.

A crucial kinetic issue for osteoarthritis is the varus-valgus moment on the knee. The medial compartment of the tibiofemoral joint is predominately affected by OA and this is related to greater tendency of external varus alignment of the knee causing increased compression forces on the medial compartment. If the vertical ground reaction force is medial to the knee joint center and/or the shear ground reaction force is medially directed, this creates a external varus moment that must be balanced by increased internal valgus moments for dynamic equilibrium. An increased internal valgus moment may help to “unload” the medial tibiofemoral compartment. In the present study, moment patterns showed a non-significant trend to increase in the internal valgus knee moment during the step up task. This may be considered a positive effect because it is a response to an external varus (adduction) moment, which has been shown to be increased in OA patients (Sharma, Hurwitz et al. 1998; Baliunas, Hurwitz et al. 2002). In addition, while not statistically significant, the increasing trend in net hip moments may have implications for the knee as well (Souza and Powers 2009; Souza and Powers 2009). For example, hip muscles may stabilize the pelvis during gait in ways to maintain the center of mass in alignment, which may have an effect on frontal plane knee moments as suggested by Bennell (Bennell, Hunt et al. 2007). However, this has not been shown experimentally.

While the small sample size and variability are limiting factors, the findings of this pilot study offer perspectives to the link between presumed and real effects of strength training on a select patient group and the mechanisms underlying some of the observed therapeutic benefits. The minimal impairments and pre-training strength of subjects may have also minimized potential changes. Including weaker or more advanced OA patients might have magnified potential changes. The greater changes in the actual dynamic training loads reached after strength training compared to the MVIC tests are most likely related to the closeness of the test to the actual exercise training and reflects the principle of specificity of training.

Conclusions

The results of this study suggest that patients with mild OA of the knee report improvements in function, pain, and other symptoms, as a result of a supervised eight-week strength training program. The participants tolerated the intensive progressive resistance exercise program well, and showed significant strength gains with no exacerbations of symptoms reported. While there were some small trends toward some adaptive changes in motor strategies for stepping, there were no significant changes in net joint moments, or specific muscle activation patterns such as the level of co-contraction of the Quadriceps and Hamstring muscles. Given the general acceptance of the importance of strengthening exercises for OA, even with specific subset limitations, and suggested by Sharma. It is important to continue to investigate direct mechanistic relationships between the improvement of strength and potential biomechanical adaptations. Our study suggests that while improving strength results in improvements in self-report measures of pain and function these improvements may not be related to strong specific biomechanical adaptations such as changes in joint moments, distribution of the total support moment or Muscle activation levels during a step-up activity

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Figure 1.
Subject Set up with reflective markers and Instrumented step

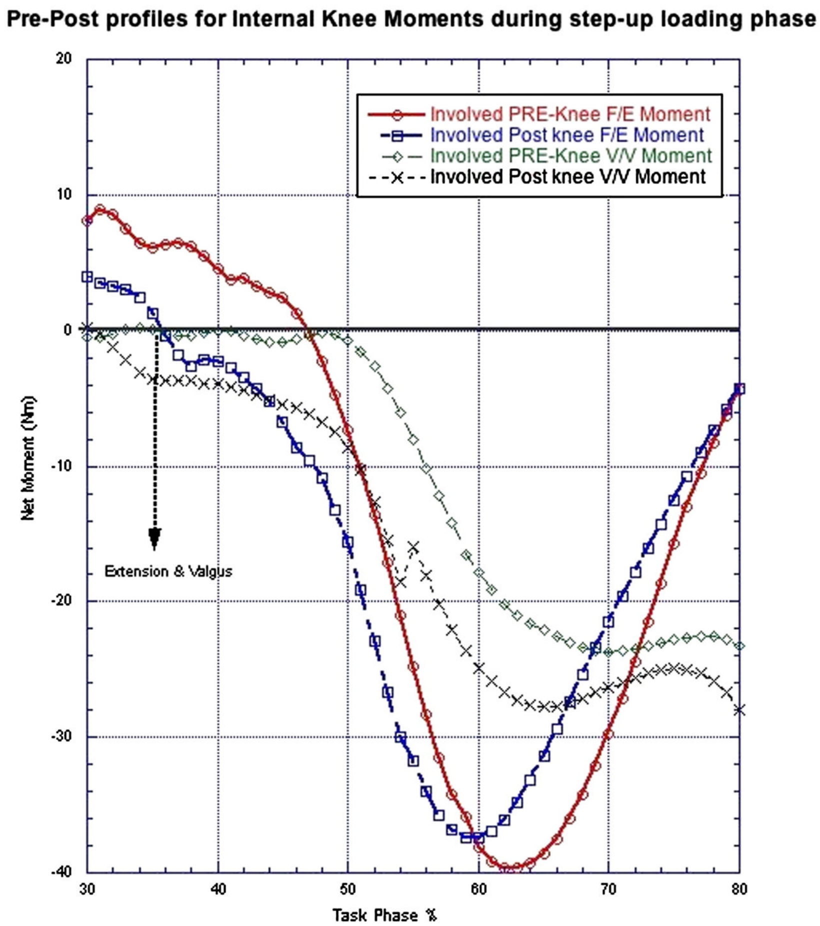

Figure 2.

Average net internal knee joint moments pre = before strength training program and post = after strength training program for involved side F/E= knee flexion/extension, V/V = knee Varus/Valgus (n=18).

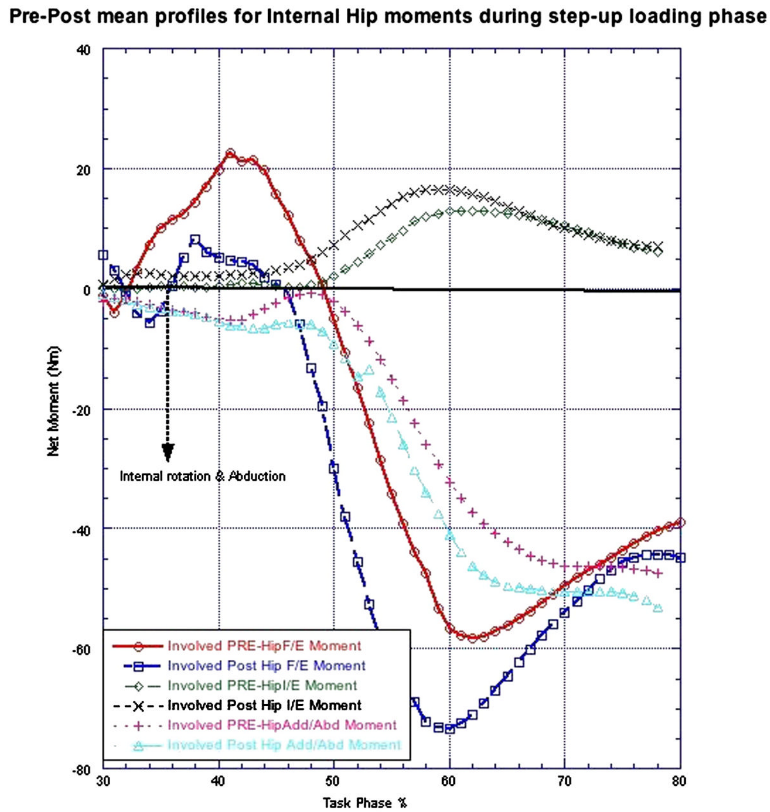

Figure 3.

Average net internal hip joint moments pre = before strength training program and post = after strength training program for involved side (n=18). F/E= flexion extension, I/E = internal/external hip rotation, Add/Abd = hip adduction/abduction

Table 1

Demographic characteristics and strengthening measures for participants (n=18).

Demographic Characteristics	Pre-Intervention	Post-Intervention	P-Value*
Age (years), Mean (s.d.)	55.8 (5.8)	NA	NA
Height (m), Mean (s.d.)	1.65 (0.1)	NA	NA
Mass (kg), Mean (s.d.)	80.8 (19.0)	NA	NA
Body Mass Index(kg/m^{2}), Mean (s.d.)	30.4 (8.5)	NA	NA
MVIC Ipsilateral Leg			
Knee Extension (Nm), Mean (s.d.)	252.7 (91.7)	304.5 (101.0)	
Median (Range)	255.1 (149.7–530.7)	273.4 (180.3–597.8)	0.002
Knee Flexion (Nm), Mean (s.d.)	145.4 (40.2)	149.4 (39.8)	
Median (Range)	138.8 (86.7–232.0)	149.3 (85.5–222.8)	0.065
Ten-Repetition Maximum Tests**			
Knee Extension (Kg), Mean (s.d.)	20.0 (7.6)	30.8 (11.4)	
Median (Range)	19.4 (9.7–45.2)	29.1 (16.1–64.6)	<.001
Knee Flexion (Kg), Mean (s.d.)	20.5 (6.4)	29.0 (7.2)	
Median Range	21.0 (8.1–38.8)	28.1 (14.2–48.5)	<.001
Leg Press (Kg, Mean (s.d.)	46.7.0 (14.3)	62.6 (18.5)	
Median (Range)	42.0 (18.1–64.6)	64.6 (34.2–97.0)	<.001

*P-value from Wilcoxon Signed Ranks Test

Table 2

Median and range values calculated from KOOS used to compare the pre- and post-intervention effects. n=18

KOOS Measures	Pre-Intervention Median (Range)	Post-Intervention Median (Range)	P-Value*
Pain	66.7 (41.7–100.0)	80.6 (52.8–100.0)	0.008*
Symptoms	64.3 (28.6–96.4)	75 (25.0–100.0)	0.01*
Activities of Daily Life	76.5 (45.6–100.0)	91.2 (67.6–100.0)	0.02*
Sports/Recreation	40 (0.0–100.0)	40 (0.0–100.0)	0.28
Quality of Life	43.7 (25.0–100.0)	56.3 (18.7–100.0)	0.01*

*P-value from Wilcoxon Signed Ranks Test

Table 3

Median and range values calculated from Knee contact forces, Peak Moments and normalized EMG used to compare the pre- and post-intervention effects on biomechanical outcomes. n=18

Outcome Measures	Pre-Intervention	Post-Intervention	P-Value*
Peak Step-up Moments for Involved Limb			
Hip Flex/Extension (Nm)	90.8 (36.2–126.8)	90.7 (42.0–169.2)	0.2
Hip I/E Rotation (Nm)	18.7 (6.7–35.0)	21.1 (8.7–34.4)	0.05
Hip Add/Abduction (Nm)	51.7 (33.8–95.6)	58.7 (36.1–90.0)	0.09
Knee Flex/Extension (Nm)	15.5 (17.2–71.3)	18.2 (19.8–80.6)	0.65
Knee Varus/Valgus (Nm)	33.3 (16.9–47.5)	37.9 (15.3–55.2)	0.08
Ankle Flex/Extension (Nm)	19.3 (12.0–82.5)	31.2 (13.7–54.5)	0.35
Electromyography Measures#			
Hamstring (NetArea)	0.12 (0.066–291)	0.11 (0.074–262)	0.51
Quadriceps (NetArea)	0.17 (0.104–314)	0.15 (0.103–305)	0.73
H/Q Ratio	0.71 (0.207–1.73)	0.62 (0.335–1.88)	0.59

Hip I/E Rotation – Hip Internal/External Rotation

#Hamstrings was represented by the mean profile for both Biceps Femoris + Semitendinosis. The Quadriceps activity was represented by the mean activity of the Rectus Femoris + Vastus lateralis + Vastus Medialis

*P-value from Wilcoxon Signed Ranks Test

Table 4

Mean and standard deviation of the percent distribution of net joint extensor moments to the total support moment (TSM) before and after training as an indicator of motor strategy changes. n=18

	Ankle % TSM	Knee % TSM	Hip % TSM	TSM =Sum
Pre-Training				
Mean (s.d.)	11.37 (8.1)	35.67 (14.6)	52.95 (11.8)	= 100%
Post-Training				
Mean (s.d.)	8.94 (6.0)	34.23 (15.2)	56.81 (12.7)	=100%