

KNEE STRENGTH AND KNEE ADDUCTION MOMENTS FOLLOWING ARTHROSCOPIC
PARTIAL MENISCECTOMY

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Running title: Knee strength and gait following meniscectomy

Abstract

Purpose:

This study investigated the relationship between muscular strength about the knee and knee joint moments during gait in patients who had undergone arthroscopic partial meniscectomy (APM).

Methods:

102 APM patients and 42 age-matched, non-operated controls underwent strength testing and 3D gait analysis. Patients were divided into weak and normal subgroups and compared with controls for spatiotemporal, kinematic and kinetic gait parameters.

Results:

Spatiotemporal parameters, kinematics and sagittal plane kinetics were similar between APM patients and controls. The APM group displayed weaker concentric knee extension and flexion strength compared to controls. The weak APM subgroup had an increased average knee adduction moment over stance, compared to the APM subgroup with normal strength levels. The weak APM subgroup also had larger peak knee adduction moments in early stance, compared to controls.

Conclusion:

Achieving normal lower limb muscle strength following APM appears important to resume normal frontal plane loading of the knee while walking.

Keywords: quadriceps; weakness; gait; osteoarthritis

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Introduction

Paragraph Number 1. Larger than normal knee adduction moments during gait have been associated with the incidence (3), severity (26) and rate of progression of tibiofemoral osteoarthritis (20). The mechanism by which cartilage degeneration develops is believed to involve loading factors that alter the mechanical environment of the cartilage. In particular, the knee adduction moment during gait has been noted for its potential role in the pathogenesis of knee osteoarthritis (1, 3, 14, 25). The knee adduction moment influences the mediolateral distribution of load across the tibial plateau, such that large adduction moments concentrate load on the medial tibiofemoral compartment. It is theorized that these larger than normal adduction moments lead to increased load on the medial aspect of the tibiofemoral joint, altering the mechanical state of the cartilage and subchondral bone, and leading to osteoarthritic changes. While prospective data to support the relationship between knee adduction moments and the development of knee joint osteoarthritis are lacking in the literature, we have recently found larger than normal knee adduction moments during walking in arthroscopic partial meniscectomy (APM) patients at 11 weeks post-surgery (36), a population who are at increased risk of early-onset knee osteoarthritis (7).

Paragraph Number 2. Muscles play an important role in controlling joint moments via their action as actuators and brakes. The quadriceps contribute the majority of support in the frontal plane while walking, particularly during early stance (28). It has been shown that coactivation of the quadriceps and hamstring muscle groups supports up to 85% of static

adduction loads placed on the knee (17). Quadriceps strength deficits have been reported for many knee pathologies, including osteoarthritis (29), ACL injured patients (33) and meniscectomy patients up to 4 years post-surgery (9, 10, 11, 18), which may contribute to poor stabilisation of frontal plane loading of the knee during gait. Herzog and Longino (12) have provided pilot data that suggested as little as 4 weeks of experimentally induced knee extensor muscle weakness can yield initial signs of joint degeneration in the knees of rabbits.

Paragraph Number 3. The quadriceps muscles also control sagittal plane loading of the knee joint during gait (8, 16). Lewek and colleagues (16) reported a reduced external knee flexion moment for weak ACL reconstruction patients (<80 % of uninjured knee extension strength), compared to those with normal knee strength (>90 %). Similarly, Rudolph et al. (24) found external knee flexion moments to be positively correlated with quadriceps strength in unstable ACL deficient patients ($r=0.765$, $p=0.030$). These findings were in association with reduced range of knee motion and suggested to interfere with the normal ability of the knee to absorb shock during weight acceptance, thereby increasing the likelihood of joint degeneration. However, there is not currently any evidence for the role of sagittal plane motion and moments in the development of knee osteoarthritis.

Paragraph Number 4. The purpose of this study was to investigate the relationship between muscular strength about the knee and knee joint moments during gait in patients who had undergone APM. It was hypothesised that APM patients would have reduced knee extensor strength compared to a healthy, age-matched control group. It was also hypothesised that patients

with strength deficits would walk with reduced knee flexion motion, reduced external knee flexion moments, and increased external knee adduction moments, compared to those with normal strength levels.

Methods

Paragraph Number 5. The APM group comprised 102 patients (87 males) aged 17-51 years, who were on average 11 weeks (SD 4.3) post-surgery ([resection of the injured region of the meniscus](#)). The control group comprised 42 adults (25 males) aged 24 to 56 years. All subjects were screened and excluded if they had radiographic evidence of knee osteoarthritis, with surgery reports also used to screen APM subjects. All subjects were further screened for: previous or current back, hip, knee or ankle joint disease, pain or injury (including previous meniscus tear); any form of arthritis; diabetes; cardiac, circulatory or neurological conditions; multiple sclerosis; stroke; lower limb fractures; bone or joint conditions; and any other disease or injury that may affect gait patterns or predispose to knee osteoarthritis. The study was approved by the Human Research Ethics Committee at the University of Western Australia and informed, written consent was obtained from all subjects prior to their participation in the study.

Paragraph Number 6. Forty five percent of the APM group had surgery on the left knee, while 55% had a right knee meniscectomy. Medial meniscectomy was performed in 79% of the patient group; lateral meniscectomy was performed on 17%, while 4% had both menisci surgically treated. Results were similar for subjects with medial versus lateral meniscectomy and their data were therefore pooled. The majority of APM subjects had sustained an injury to the

posterior horn of the meniscus, with only three subjects having surgery performed for an anterior horn injury.

Paragraph Number 7. All subjects had physical activity levels, knee strength and gait patterns assessed. Physical activity levels were measured using a Computer Science and Applications Inc. (Actigraph, Fort Walton Beach, FL) physical activity monitor. The monitor was worn by each subject for seven days, carried on an adjustable belt that was secured firmly over the iliac crest (Figure 3.1). Subjects wore the monitor for 7 day and the average daily hours of physical activity was determined. Subjects were tested for isometric and isokinetic concentric knee strength, using a Biodex dynamometer (Biodex Medical, Shirley, NY). Strength testing was performed on the APM subject's affected limb, while a limb was randomly selected for control subjects, resulting in 43% left and 57% right knees analyzed. Isometric knee flexion and extension strength was tested at 75° and 45° of knee flexion, respectively. Concentric knee flexion and extension strength was measured through a range of 0° to 90° of knee flexion at 180°·sec⁻¹. Warm-up exercises were performed prior to strength testing and subjects were given adequate rest between trials to minimize fatigue. Subjects were verbally encouraged during the test and each was repeated at least twice to ensure a maximum effort was achieved.

Paragraph Number 8. Three-dimensional gait analysis was conducted at subjects' freely-chosen walking speed. A custom seven-segment 'cluster' model was used to estimate hip, knee, and ankle kinematic and kinetic data (6), utilizing data collected from a 50 Hz VICON motion analysis system (Oxford Metrics, Oxford, UK) and two AMTI force plates operating at 2000 Hz

(AMTI, Watertown, MI). Gait analysis data were analyzed as we have previously described (31, 32, 36). Gait velocity ($\text{m}\cdot\text{sec}^{-1}$) was measured from the pelvis centre averaged over the three-second data collection period. Stride length (m) and step width (m) were measured between right and left calcaneal markers in the sagittal and frontal planes, respectively. Kinematic parameters analyzed were: knee angle at heel strike; peak knee flexion during weight acceptance; peak knee extension during late stance; and knee range of motion (ROM). Knee ROM was calculated as the excursion of the knee angle from heel strike to peak knee flexion in the weight acceptance phase of stance. Kinetic parameters analysed were: peak knee flexion moment during early stance; peak knee extension moment during late stance; peak knee adduction moment during early stance; minimum knee adduction moment during midstance; peak knee adduction moment during late stance; and average adduction moment over stance. Knee moments were expressed as external moments applied to the joint.

Paragraph Number 9. Strength data were normalized by removing the slope of the slope of the relationship between the moment and body weight \times height from the moment data. APM subjects were classified into either 'Weak' or 'Normal' knee extension strength. APM subjects with normalized isometric knee strength more than one standard deviation below the mean of the control group were classified as 'Weak', with all others classified as 'Normal'. The isometric tests of strength were a less discriminating measure of knee strength than were isokinetic tests, with APM patients performing relatively better on isometric measures. In fact, Stam et al. (34) has previously demonstrated that isokinetic testing is more sensitive for small strength differences than isometric testing in meniscectomy patients. We categorized patients based on

their isometric knee extension strength, confident that this was a more moderate measure to reliably differentiate between groups. The Weak subgroup demonstrated significantly poorer performances in all strength tests, compared to APM Normal and controls, indicating that our criterion was appropriate to categorize the Weak.

Paragraph Number 10. Between-group differences in age, height and weight variables were examined using t-tests. Strength and gait data were statistically tested using ANCOVA, with body weight and height entered as covariates. Scheffe post-hoc tests were used to determine the significance of interactions. Relationships between strength variables were tested using Pearson Product-Moment Correlations. The level of significance was set at $p=0.05$.

Paragraph Number 11. There were no between-group differences in subject height and age, yet the APM patients were, on average, heavier than controls. A common method to control for this difference while examining kinetic data is to divide the moment variable by body weight (refs), although this has associated problems. If one assumes the moment term (M) has a linear relationship with body weight (BW), this can be written as $M = mBW + c$, where m and c are the constants of the linear function. Dividing by BW , the equation becomes $M/BW = m + c/BW$, resulting in the normalized moment, M/BW , having a residual correlation of c/BW , with M/BW becoming smaller as BW increases (21). The relationships between BW and each of the moment parameters in from the control and APM groups were analyzed using GraphPad Prism (Windows version 5.01, GraphPad Software, San Diego, USA) and showed similar regression slopes between-groups ($p>0.429$), however the y-intercepts were non-zero ($p<0.002$). Therefore,

we chose to control for the confounding influence of BW through its inclusion as a covariate in the statistical analyses as this accounts for the residual relationship between the BW and joint moments.

Results

Paragraph Number 12. Control and APM groups recorded similar levels of physical activity ($p=0.422$). APM subjects categorized as Weak had significantly reduced levels of physical activity, compared to those categorized with normal strength ($p=0.019$) (Table 1). APM Normal and APM Weak had similar self-reported knee pain and function levels ($p=0.540$), as determined by the Knee Osteoarthritis Outcome Survey (Roos et al., 1998). Both subgroups reported similar (low) levels of pain ($p=0.407$).

Paragraph Number 13. While controlling for body weight and age, the concentric knee extension strength of the APM group was less than the control group ($p<0.001$), while isometric strength was reduced in the APM patients compared to controls ($p=0.029$) (Table 1). Concentric knee flexion strength of the APM group was less than controls ($p=0.006$), while isometric knee flexion strength was similar between groups ($p=0.531$).

Paragraph Number 14. Compared to the mean knee extension strength of the control group, 27% of the APM subjects were classified as Weak based on isometric knee extension. The Control, APM Normal and APM Weak were similar in height. The APM Weak subgroup

was significantly older and heavier than Controls (Table 1). Again, we statistically adjusted for age and body weight by using these variables as covariates in the statistical analyses.

Paragraph Number 15. Walking speed, stride length, and step width were similar between control, APM Normal, and APM Weak, categorized by knee extensor strength (Table 2). Sagittal plane knee kinematics were also similar between groups. While controlling for body weight and age, peak knee flexion and extension moments were not significantly different between Control, Normal and Weak knee extensor APM subgroups (Figure 1).

Paragraph Number 16. While controlling for body weight and age, APM Weak subjects walked with larger average knee adduction moments over stance, compared to APM Normal ($p=0.011$) and control ($p=0.033$) (Figure 2). Furthermore, the first peak of the knee adduction moment was greater for APM Weak, compared to APM Normal ($p=0.032$) and control ($p=0.005$). APM Weak also showed a trend for a larger adduction moment midstance trough, compared to APM Normal ($p=0.050$). The peak knee adduction moment during late stance was significantly greater for APM Weak, compared to APM Normal ($p=0.020$). APM Normal subjects had significantly greater adduction moment peak in early stance, compared to control ($p=0.005$).

Discussion

Paragraph Number 17. The knee adduction moment during the stance phase of gait has been implicated as a mechanical factor contributing to the development of knee osteoarthritis.

We have recently shown larger-than-normal knee adduction moments within the gait patterns of patients who have undergone APM (36), a population at increased risk of early onset of knee osteoarthritis (7). This study aimed to examine associations between muscular strength about the knee and moments acting at the knee during gait in an APM population.

Paragraph Number 18. The APM group produced reduced knee extension strength, compared to Controls (Table 1), supporting the first hypothesis. These results are consistent with previous research that found knee extensor strength deficits in a group of ten post-APM patients, compared to a group of matched healthy subjects, pre-operatively and at three and eight weeks post-operatively (9). In fact, quadriceps weakness has been shown to persist at 12 weeks (18), 6 months (11) and 4 years post-APM (10). Furthermore, concentric knee extensor strength deficits of ~20% have been shown to persist, even after eight-weeks of knee strength training in post-meniscectomy patients (34). The APM group was also weaker in tests of knee flexion, indicating a general muscle weakness about the knee, perhaps due to reduced levels of physical activity. While tests of strength were only conducted at the knee joint, APM are likely to have a general lower limb weakness. Persistent muscle weakness following meniscectomy may contribute to gait abnormalities, compromise joint stability, and have detrimental effects on the maintenance of healthy cartilage by altering the mechanical environment of the tissue. In rabbits, quadriceps weakness that was experimentally induced for 4 weeks resulted in functional deficits and evidence of knee joint degeneration (12), suggesting that muscle weakness may act as an independent causative factor for knee osteoarthritis. Muscle atrophy via disuse following APM may similarly initiate cartilage degeneration in humans and alter the mechanical environment of

the knee joint. Slemenda and colleagues (1998) showed females who developed incident knee OA after 31 months had 18% lower knee extensor strength than female controls at baseline ($p=0.053$).

Paragraph Number 19. Sagittal plane kinematics and kinetics were similar between APM Normal, APM Weak and Control groups (Table 2, Figure 1), which was inconsistent with our hypothesis that the APM subgroup with reduced knee extension strength would also exhibit a reduced range of knee flexion and reduced knee flexion moments. The quadriceps and hamstrings weakness seen in the Weak APM group had no substantial effect on sagittal plane motion and loading. Contrasting results have been reported for populations with ACL injury (8, 16, 24) and those with knee arthritis (5, 35). The absence of a similar association in our meniscectomy population is likely due to the relatively good joint function, low pain and other symptoms that lead to reduced knee flexion in other patients groups.

Paragraph Number 20. The results of this study supported our hypothesis that larger frontal plane knee moments exist in meniscectomy patients with knee extensor weakness. Compared to APM patients with normal knee extensor strength, the weak APM patients had larger knee adduction moments over stance (Figure 2). These results indicate that weak APM patients walk with increased force on the medial compartment of the tibiofemoral joint (25), a common site for osteoarthritis in this population (15). Animal studies have shown site-specific initiation of degenerative changes to articular cartilage (38) in response to short-term high loading, while in humans, dynamic load on the medial compartment can predict radiographic

progression of osteoarthritis (20). Andriacchi and colleagues (1, 2) suggest that initiation of osteoarthritis is associated with a shift in ambulatory loads to regions that are unable to adequately adapt, leading to cartilage damage and establishing an environment for progression of osteoarthritis. In view of this evidence, we suggest that weak APM patients, in particular, are at increased risk of developing knee osteoarthritis; a hypothesis that requires investigation via a prospective study.

Paragraph Number 21. Evidence exists to implicate muscle weakness in the onset and progression of knee osteoarthritis. Reduced quadriceps strength is predictive of both radiographic and symptomatic osteoarthritis of the knee (12) (4, 13, 29). Slemenda and colleagues (30) found women who developed incident knee osteoarthritis over a period of ~2.5 years were 18% weaker in knee extensor strength at baseline than those who did not develop osteoarthritis. It has been speculated that quadriceps weakness contributes to the development of knee osteoarthritis via reduced shock absorption during impulse loading at heel strike (19, 23, 27). Weak quadriceps may also contribute to knee osteoarthritis via increased knee adduction moments across the stance phase of ambulation. This study has shown APM patients with weak knee extensors have larger knee adduction moments than controls, a feature of gait that is predictive of knee osteoarthritis (20). However, this study assessed strength only in knee flexion and extension and normal knee flexion and extension moments in the Weak APM suggest the knee extensors are effective in this plane. The premise for examining associations between knee extensors and knee adduction moments was based on work by Shelburne et al. (28), which showed quadriceps supported much of the knee adduction moment while walking. Other muscles have the potential

to influence knee adduction moments, however (17, 28). The position of the knee relative to the ground reaction force vector will determine the moment arm about this joint, so that motion of the centre of mass in the mediolateral plane can alter the knee adduction moment. Control of the centre of mass position is likely to play a large role in the size of the knee adduction moment. Indeed, larger hip abductor moments (indicative of hip adductor muscle forces) are associated with reduced knee adduction moments (Mundermann a,b). The gastrocnemii may also support the knee adduction moment during late stance (28). Our findings that meniscectomy patients with weak knee extensor strength have larger knee adduction moments may be indicative of an overall lower limb weakness affect on adduction moments.

Paragraph Number 22. We have reported strength deficits and gait patterns in APM patients, on average, 11 weeks post-surgery. With longer recovery time, patients may recover knee strength and regain normal gait patterns, eliminating the increased risk of knee osteoarthritis that has been speculated here. At 6 months post-APM an isokinetic knee extensor strength deficit of 18% has been observed in the operated leg, compared to the non-operated leg (11) with a 9% deficit seen at 4 years (10). If rabbit knees show cartilage defects after only 4 weeks of quadriceps weakness (12), the period of quadriceps weakness in APM patients may be adequate for the associated loading characteristics to alter the mechanical properties of the articular cartilage to a point that is susceptible to damage from additional load (1, 2). Longitudinal studies are required to examine the relationship between knee strength and gait patterns over time in an APM population and their influence on the development of knee osteoarthritis. The potential role of muscular weakness and large knee adduction moments in the

mechanism of the initial meniscal injury should also be examined as this cross sectional study does not refute the possibility that the differences observed in strength and gait patterns of the APM patients existed prior to the meniscal injury.

The menisci provide improved articulation for the medial and lateral tibiofemoral joints. Removal of part of the meniscus alters this physical environment and although there is no evidence that partial meniscectomy affects lower limb alignment. This study did not examine differences related to the amount or area of the excised meniscus, which should be considered in future work. However, we found no differences in frontal leg alignment between Normal and Weak APM subgroups ($p=0.554$), as measured the angle between mechanical axes of the femur and tibia.

Paragraph Number 23. Following an APM, individuals experience larger than normal knee adduction moments during gait (36), which are particularly great in patients with reduced knee extension strength. As the knee adduction moment tends to load the medial articular surface of the tibiofemoral joint, and is implicated in the progression of knee joint degeneration, APM patients with quadriceps weakness may be at particular risk of developing knee osteoarthritis (20, 22, 37). Retaining muscle strength following meniscectomy should be a priority in a patient's recovery from surgery. Further indicating the importance of restoring strength is the report of quadriceps weakness at 4 years post-APM, which significantly affects knee function, pain, and quality of life (10). We suggest, therefore, that post-APM patients would likely benefit from an

intervention aimed at increasing lower limb strength, to improve knee loading patterns, pain and function.

Acknowledgments

Paragraph Number 24. We acknowledge the financial support of the NHMRC (Grants #991134 and #254565 to DGL, GWS and KFM) and Western Australian Medical Research Infrastructure Fund (to DGL). Thanks to Mr Alec Buttfield, Ms Catherine Hill, Ms Donna Ferguson, Mr Rob King, Mr Chris Winby and Mr Shane Ilich for assistance with data collection and processing. Thanks to the following surgeons for their support in recruiting patients: Mr Keith Holt, Mr Greg Witherow, Mr Greg Janes, Mr Peter Annear, Mr Hari Goonatillake, Mr Dermot Collopy, Mr David Colvin, Mr Peter Campbell. Thanks to Dr Stephen Davis and Ms Simone Mattfield for assistance in the radiology clinic.

Conflict of Interest

Paragraph Number 25. There are no conflicts of interest or professional relationships with companies or manufacturers who will benefit from the results of the present study. The results of the present study do not constitute endorsement of the product by the authors or ACSM.

References

1. Andriacchi TP, Mundermann A. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Curr Opin Rheumatol* 2006;18(5):514-8.
2. Andriacchi TP, Mundermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng* 2004;32(3):447-57.
3. Baliunas AJ, Hurwitz DE, Ryals AB, Karrar A, Case JP, Block JA, Andriacchi TP. Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis Cartilage* 2002;10(7):573-579.
4. Barker K, Lamb SE, Toye F, Jackson S, Barrington S. Association between radiographic joint space narrowing, function, pain and muscle power in severe osteoarthritis of the knee. *Clin Rehabil* 2004;18(7):793-800.
5. Bennell KL, Hinman RS, Metcalf BR. Association of sensorimotor function with knee joint kinematics during locomotion in knee osteoarthritis. *Am J Phys Med Rehabil* 2004;83(6):455-63.
6. Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait analysis variables using a marker cluster model and functional determination of joint centres and axes. *J Biomech* 2003;36:1159-68.
7. Bolano LE, Grana WA. Isolated arthroscopic partial meniscectomy. Functional radiographic evaluation at five years. *Am J Sports Med* 1993;21(3):432-7.

8. Ciccotti MG, Kerlan, R. K., Perry, J., Pink, M. An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament-deficient and -reconstructed profiles. *Am J Sports Med* 1994;22(5):651-8.
9. Durand A, Richards CL, Malouin F. Strength recovery and muscle activation of the knee extensor and flexor muscles after arthroscopic meniscectomy. A pilot study. *Clin Orthop* 1991(262):210-26.
10. Ericsson YB, Roos EM, Dahlberg L. Muscle strength, functional performance, and self-reported outcomes four years after arthroscopic partial meniscectomy in middle-aged patients. *Arthritis Rheum* 2006;55(6):946-52.
11. Gapeyeva H, Paasuke M, Ereline J, Pintsaar A, Eller A. Isokinetic torque deficit of the knee extensor muscles after arthroscopic partial meniscectomy. *Knee Surg Sports Traumatol Arthrosc* 2000;8(5):301-4.
12. Herzog W, Longino D. The role of muscles in joint degeneration and osteoarthritis. *J Biomech* 2007;40:S54-S63.
13. Hurley MV, Scott DL, Rees J, Newham DJ. Sensorimotor changes and functional performance in patients with knee osteoarthritis. *Ann Rheum Dis* 1997;56(11):641-8.
14. Hurwitz DE, Ryals AB, Case JP, Block JA, Andriacchi TP. The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain. *J Orthop Res* 2002;20(1):101-107.

15. Kruger-Franke M, Siebert CH, Kugler A, Trouillier HH, Rosemeyer B. Late results after arthroscopic partial medial meniscectomy. *Knee Surg Sports Traumatol Arthrosc* 1999;7(2):81-4.
 16. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon)* 2002;17(1):56-63.
 17. Lloyd DG, Buchanan TS. Strategies of the muscular contributions to the support of static varus and valgus loads at the human knee. *J Biomech* 2001;34(10):1257-1267.
 18. Matthews P, St-Pierre DM. Recovery of muscle strength following arthroscopic meniscectomy. *J Orthop Sports Phys Ther* 1996;23(1):18-26.
 19. Mikesky AE, Meyer A, Thompson KL. Relationship between quadriceps strength and rate of loading during gait in women. *J Orthop Res* 2000;18(2):171-5.
 20. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Ann Rheum Dis* 2002;61(7):617-22.
- {Mundermann, 2005 #42}
- {Mundermann, 2007 #43}
21. O'Malley MJ. Normalization of temporal-distance parameters in pediatric gait. *J Biomech* 1996;29(5):619-25.
 22. Prodromos CC, Andriacchi TP, Galante JO. A relationship between gait and clinical changes following high tibial osteotomy. *J Bone Joint Surg Am* 1985;67(8):1188-94.

23. Ramsey DK, Snyder-Mackler L, Lewek M, Newcomb W, Rudolph KS. Effect of anatomic realignment on muscle function during gait in patients with medial compartment knee osteoarthritis. *Arthritis Rheum* 2007;57(3):389-97.
24. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc* 2001;9(2):62-71.
25. Schipplein OD, Andriacchi TP. Interaction between active and passive knee stabilizers during level walking. *J Orthop Res* 1991;9(1):113-9.
26. Sharma L, Hurwitz DE, Thonar EJ, et al. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis Rheum* 1998;41(7):1233-40.
27. Sharma L, Lou C, Felson DT, et al. Laxity in healthy and osteoarthritic knees. *Arthritis Rheum* 1999;42(5):861-70.
28. Shelburne KB, Torry MR, Pandy MG. Contributions of muscles, ligaments, and the ground-reaction force to tibiofemoral joint loading during normal gait. *J Orthop Res* 2006;24(10):1983-90.
29. Slemenda C, Brandt KD, Heilman DK, et al. Quadriceps weakness and osteoarthritis of the knee. *Ann Intern Med* 1997;127(2):97-104.
30. Slemenda C, Heilman DK, Brandt KD, et al. Reduced quadriceps strength relative to body weight: a risk factor for knee osteoarthritis in women? *Arthritis Rheum* 1998;41(11):1951-9.

31. Smith AJ, Lloyd DG, Wood DJ. Pre-surgery knee joint loading patterns during walking predict the presence and severity of anterior knee pain after total knee arthroplasty. *J Orthop Res* 2004;22(2):260-6.
32. Smith AJ, Lloyd DG, Wood DJ. A kinematic and kinetic analysis of walking after total knee arthroplasty with and without patellar resurfacing. *Clin Biomech (Bristol, Avon)* 2006;21(4):379-86.
33. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am* 1995;77(8):1166-73.
34. Stam HJ, Binkhorst RA, Kuhlmann P, van Nieuwenhuyzen JF. Clinical progress and quadriceps torque ratios during training of meniscectomy patients. *Int J Sports Med* 1992;13(2):183-8.
35. Stauffer RN, Chao EYS, Gyory AN. Biomechanical gait analysis of the disease knee joint. *Clin Orthop Relat Res* 1977;126:246-255.
36. Sturnieks DL. Variations in gait patterns and recovery of function following arthroscopic partial meniscectomy [dissertation]. Perth, Western Australia: The University of Western Australia; 2004. 376 p.
37. Wang JW, Kuo KN, Andriacchi TP, Galante JO. The influence of walking mechanics and time on the results of proximal tibial osteotomy. *J Bone Joint Surg Am* 1990;72(6):905-9.

38. Wu DD, Burr DB, Boyd RD, Radin EL. Bone and cartilage changes following experimental varus or valgus tibial angulation. *J Orthop Res* 1990;8(4):572-85.

Table 1. Group mean (SD) characteristics for Control, APM Normal and APM Weak. Normal and Weak subgroups were classified according to their isometric knee extension strength.

Table 2. Group mean (SD) spatiotemporal and kinematic gait parameters for Control, APM Normal and APM Weak. Normal and Weak subgroups were classified according to their isometric knee extension strength.

Figure 1. Normalized mean (SE) peak knee flexion and extension moments during stance phase of gait in controls and APM subjects categorized with Normal and Weak knee extension strength.

Figure 2. Normalized mean (SE) knee adduction moments over stance phase of gait in Control subjects and APM subjects categorized with Normal and Weak knee extension strength.

* $p < 0.05$ versus Control. # $p < 0.05$ versus Normal.