**Title:** Mechanisms underpinning the peak knee flexion moment increase over 2-years following arthroscopic partial meniscectomy

**Authors**: Michelle Hall[1], Tim V Wrigley[1], Ben R Metcalf[1], Rana S Hinman[1], Flavia M Cicuttini[4], Alasdair R Dempsey[2,3], Peter M Mills[2], David G Lloyd[2], Kim L Bennell[1]

**Affiliations:** [1]Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, School of Health Sciences, Melbourne, The University of Melbourne, VIC Australia

[2] Centre for Musculoskeletal Research, Menzies Health Institute Queensland, Griffith University, Gold Coast Campus, QLD Australia

[3] School of Psychology and Exercise Science, Murdoch University, Perth, WA Australia

[4] Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC Australia

**Corresponding author:**

Kim L Bennell
Centre for Health, Exercise and Sports Medicine
Department of Physiotherapy
The University of Melbourne
Victoria, 3010, Australia
Tel: +61 3 8344 4135
Fax: +61 3 8344 4188
Email: k.bennell@unimelb.edu.au

**Running title:** knee flexion moment, partial meniscectomy

**Abstract word count: 250**

**Main text word count: 3768**

**CONFLICT OF INTEREST**

No authors have a conflict of interest.

**ABSTRACT:**

*Background:* Knee osteoarthritis is common in people who have undergone partial meniscectomy, and a higher external knee flexion moment during gait may be a potential contributor. Although the peak external knee flexion moment has been shown to increase from 3 months to 2 years following partial meniscectomy, mechanisms underpinning the increase in the peak knee flexion moment are unknown.

*Methods:* Sixty-six participants with partial meniscectomy completed three-dimensional gait (normal and fast pace) and quadriceps strength assessment at baseline (3 months following partial meniscectomy) and again 2 years later. Variables included external knee flexion moment, vertical ground reaction force, knee flexion kinematics, and quadriceps peak torque.

*Findings:* For normal pace walking, the main significant predictors of change in peak knee flexion moment were an increase in peak vertical ground reaction force ($R^2$ = 0.55), mostly due to an increase in walking speed, and increase in peak knee flexion angle ($R^2$ = 0.19). For fast pace walking, the main significant predictors of change in peak knee flexion moment were an in increase in peak vertical ground reaction force ($R^2$ = 0.51) and increase in knee flexion angle at initial contact ($R^2$ = 0.17). Change in peak vertical force was mostly due to an increase in walking speed.

*Interpretation:* Findings suggest that increases in vertical ground reaction force and peak knee flexion angle during stance are predominant contributors to the 2-year change in peak knee flexion moment. Future studies are necessary to refine our understanding of joint loading and its determinants following meniscectomy.

## 1.1 **INTRODUCTION**

People following APM are at increased risk of developing knee osteoarthritis in both the tibiofemoral and patellofemoral compartments (Englund and Lohmander, 2005; Wang et al., 2012). Although knee osteoarthritis is considered in part a mechanical disease (Felson, 2013), the pathogenesis of this debilitating condition is not well understood in patients following APM. Higher joint loading inferred through external knee joint moments during gait has been associated with compromised cartilage health following APM (Hall et al., 2015) as well as in those with established OA (Bennell et al., 2011; Chang et al., 2015; Chehab et al., 2014; Miyazaki et al., 2002). Although most literature highlights the role of the external knee adduction moment in structural change (Bennell et al., 2011; Chehab et al., 2014; Miyazaki et al., 2002), the external knee flexion moment (KFM) is increasingly being implicated as a factor in the pathogenesis of knee osteoarthritis (Chehab et al., 2014; Creaby, 2015; Hall et al., 2015; Teng et al., 2015).

Indeed, the peak KFM may be clinically relevant in people following APM. Three months following APM, we observed that a higher peak KFM during normal pace gait was associated with reduced patellar cartilage volume, over the subsequent 2 years (Hall et al., 2015). The peak KFM increased by approximately 13% over time, such that the peak KFM was 6-11% higher during walking in APM patients compared to healthy controls 2 years later (Hall et al., 2013). Furthermore, a higher KFM during gait has also recently been associated with medial tibial cartilage (Chehab et al., 2014) and patellofemoral joint (Teng et al., 2014) deterioration. Therefore, considering both an increase in KFM over time following APM and a potential link between higher KFM and subsequent adverse cartilage changes, the KFM may constitute a potential target for interventions aiming to preserve knee joint cartilage integrity. However, designing interventions to target the KFM requires an understanding of mechanisms responsible for the increase in peak KFM over time in individuals following APM.

The KFM during gait is predominately a product of the magnitude of the sagittal plane ground reaction force (GRF), which can be increased by a faster walking speed and greater body mass, and the sagittal plane moment arm (i.e. the perpendicular distance of the GRF vector to the knee joint center). We have previously found a significant increase in peak vertical GRF (vGRF) over 2 years in the affected leg of patients who have undergone an APM compared to healthy controls (Hall et al., 2015). Knee flexion kinematics have not been longitudinally described in patients following APM. This is important to consider as an increase in knee flexion angle may partly explain the change in peak KFM by increasing the sagittal plane GRF moment arm (Creaby et al., 2013).

The KFM moment is supported predominantly by the quadriceps (Winter, 1984), and an increase in the KFM moment is likely to place a greater demand on quadriceps function. Indeed, a lower peak KFM moment is associated with reduced knee extension strength in patients with knee osteoarthritis (Farrokhi et al., 2015) and in those following anterior cruciate ligament reconstruction (Lewek et al., 2002). We have previously reported that the quadriceps were weaker in the APM leg compared to healthy controls at 3 months following surgery (Sturnieks et al., 2008) and that quadriceps strength significantly increased in these patients over 2 years (Hall et al., 2013), As such, an increase in peak KFM over time may reflect the improvement in quadriceps strength in these patients. Although improving quadriceps strength is typically encouraged following knee arthroscopy (Panisset and Prudhon, 2012), it has not been shown that an increase in quadriceps strength is indeed associated with the peak KFM increase in these patients.

The purpose of this study in people assessed 3 months following APM (baseline) and 2-years later (follow-up) was to explore potentially modifiable biomechanical characteristics that explain the change in peak KFM over time. We hypothesized that an increase in walking speed, greater knee flexion angle during stance, an increase in vertical GRF magnitude and increase in quadriceps strength would partially explain the 2-year increase in peak KFM observed in people following APM.

## 2.0 METHODS

### 2.1 Participants

This is a further analysis of a 2-year prospective study (Hall et al., 2013). We recruited 82 participants aged between 30 and 50 years who had undergone an isolated medial APM 3 months prior. People were excluded if they had: evidence of lateral meniscal resection; greater than one third of medial meniscus resected; >2 tibiofemoral cartilage lesions; a single tibiofemoral cartilage lesion > approximately 10mm in diameter as assessed at arthroscopy; previous knee or lower limb surgery (other than the recent APM); history of knee pain (other than that leading to APM); post-operative complications; cardiac, circulatory or neuromuscular conditions; diabetes; stroke; multiple sclerosis; and/or contraindication to MRI. Participants provided written informed consent, and the local institutional Human Research Ethics Committee approved this study.

### 2.2 Gait Analysis

Kinematic data (120Hz) were acquired using a Vicon motion capture system (Vicon, Oxford, UK) with eight M2/MX CMOS cameras (1280 x 1024) while kinetic data (1080Hz) were captured in synchrony using two 0R6-6-2000 force plates and one BP-600-900 force plate (Advanced Mechanical Technology, Watertown Massachusetts, USA). A custom sevensegment lower limb direct kinematics and inverse dynamics model written in BodyBuilder (Vicon, Oxford, UK) was used to estimate lower limb joint kinematics and kinetics (Besier et al., 2003). Hip and knee joint centers and knee joint flexion/extension axes were defined as per Besier et al. (2003). Five barefoot walking trials were performed at a self-selected normal pace described as 'natural and comfortable pace', and fast pace walking described as 'if you were in a hurry'. Walking speed was measured by two photoelectric timing gates placed 4 meters part, centred on the force plates. The peak KFM was expressed as an external moment applied to the distal segment and reported for the APM limb in this study. The peak KFM in the first half of stance was recorded, averaged over five trials, and normalised to the product of body weight and height (Nm/(BW×HT)%). The test-retest reliability for the entire KFM curve has been previously reported as 0.84 (coefficient of multiple determination, $r^2$) (Besier et al., 2003). The peak vertical GRF was extracted and normalised to body weight (N/BW). Knee kinematics including flexion at initial contact, peak knee flexion during stance, and flexion excursion from initial contact to peak knee flexion were used in subsequent analysis.

2.3 Strength assessment

Maximal isokinetic quadriceps muscle strength was assessed using a Kin-Com 125-AP dynamometer (Chattecx, Chattanooga, Tennessee, USA) at baseline and follow-up. On the APM limb only, participants performed two sub-maximal warm-up efforts for familiarisation and five repetitions of reciprocal maximal concentric-concentric contractions of quadriceps and hamstrings at 60°/sec, followed by eccentric-eccentric contractions, with 40 seconds separating the two bouts. Verbal instructions were given to 'push as hard as you can'. The peak concentric and eccentric torques were recorded from five trials, and normalised to body mass (Nm/kg).

2.4 Statistical Analysis

For descriptive purposes, Pearson correlations were performed between the change (from 3 months following surgery to 2 years later) in peak KFM and change in biomechanical variables considered to theoretically influence change in peak KFM including: walking speed, body mass, knee flexion at initial contact, peak knee flexion during stance, knee flexion angle excursion, peak vGRF and knee extensor strength. To determine if these parameters predicted change in peak KFM, a forward stepwise regression was performed with each of the aforementioned parameters entered as independent variables into the model (probability entry = 0.05 and probability of removal = 0.10), with change in peak KFM as the dependent variable.

In the event that change in vGRF was found to be a significant predictor of change in peak KFM, further analyses were performed to explore the mechanisms of change in vGRF magnitude. Pearson correlations were performed to describe the relationships between change in vGRF and i) change in walking speed, ii) change in body mass and iii) change in knee flexion angle kinematics. To ascertain if these parameters were associated with change in vGRF, a forward stepwise regression was again performed with each of the aforementioned variables entered as independent variables into the model (probability entry = 0.05 and probability of removal = 0.10), but with change in vGRF as the dependent variable.

Stepwise regression models were assessed to ensure the following assumptions were satisfied including: i) approximate linear relationship between predictor variables and dependent variable; ii) normality of residuals; iii) homoscedastic variance and iv) multicollinearity was assessed using collinearity statistics where a variance inflation factor (VIF) < 4 was considerable acceptable (Peat and Barton, 2008). Outputs of interest from regression models included: standardardised coefficients (β) to provide relative strength of each predictor variable to the model; unstandardardised coefficients (B) to describe relationship between change in predictor and change in outcome (i.e. change in peak KFM), and associated R-values to describe the amount of variance of the outcome explained by predictors. SPSS (SPSS Inc., Chicago, IL, USA) was used to perform statistical analyses with an alpha level of 0.05.

## RESULTS

Eighty percent of participants returned at follow-up assessment (n=66). For normal pace walking, one participant had incomplete data and two different participants had incomplete data for fast pace walking. In total, all 66 participants were included in the analyses, with 65 included in normal pace analyses and 64 participants included in fast pace analyses. Participants evaluated were largely male ($n$ = 56; 86%) and middle-aged (mean 41.3 years, SD 5.4 years), 1.75m (SD 0.1) tall, and overweight (body mass index mean 27.28kg/$m^2$, SD 4.23). There were no significant differences in body mass between baseline (mean 83.8 kg, SD 14.4 kg) and follow-up (mean 84.02 kg, SD 15.43 kg). There was a significant increase in peak KFM, while no differences in walking speed (either fast or normal pace) was observed (Table 1). Furthermore, there were no significant differences at baseline in the study variables between participants who had complete data sets compared to the 16 participants who did not return for follow-up assessment.

### *3.1 Normal pace walking*

In simple correlational analyses, change in walking speed, change in knee flexion angle at initial contact, change in peak knee flexion angle, change in vGRF and change in quadriceps strength (concentric and eccentric) were positively related to change in peak KFM (Table 2).

Change in vGRF (*r* = 0.75) and walking speed (*r* = 0.69) had the highest significant correlations with change in KFM. Results from stepwise regression with all potential predictors (as listed in Table 2) demonstrated a high degree of collinearlity for change in knee flexion angle at initial contact (VIF = 16.04), change in peak knee flexion angle (VIF = 18.09) and change in knee flexion excursion (VIF = 18.38). Thus, given that knee flexion excursion angle is determined by subtracting the peak knee flexion angle from the minimum knee flexion angle, which is typically the knee flexion at initial contact, change in knee flexion excursion was removed as a potential predictor from the model. Of the remaining variables entered as potential predictors, the final stepwise regression model indicates that 75% of variance in peak KFM was explained by change in peak vGRF (55%), change in peak knee flexion angle (19%) and change in peak concentric quadriceps strength (2%) (Table 3). The directions of these relationships indicate that an increase in vGRF (B = 12.16; 95%CI 10.19 – 14.12), an increase in peak knee flexion angle (B = 0.15; 95%CI 0.11 – 0.20), and an increase in concentric quadriceps strength (B = 0.44; 95%CI 0.02 – 0.85) were associated with an increase in peak KFM. In descending order of relative strength of contribution to the model, the standardised coefficients indicate that change in peak GRF (β = 0.80), change in peak knee flexion angle (β = 0.43), and change in concentric strength (β = 0.13), relate to change in peak KFM respectively (Table 3).

There was a positive correlation between change in walking speed and change in peak vGRF, and a negative correlation between change in peak vGRF and i) change in knee flexion angle excursion and ii) change in body mass and (Table 4). In the regression model, 68% of the variance in vGRF was explained by change in walking speed (62%) and change in knee flexion excursion angle contributing a small, but statistically significant 6% (Table 5). The directions of these relationships indicate an increase in walking speed (B=0.47; 95% CI 0.38

– 0.56) and a decrease in knee excursion angle (B=-0.01; 95% CI -0.01 to 0.00) are associated with increase in vGRF. In descending order of relative strength of contribution to the model, the standardised coefficients indicate that change in walking speed (β = 0.76) and change in knee excursion angle (β = 0.76) contribute to change in peak GRF (Table 5).

### *3.2 Fast pace walking*

In simple correlational analyses, change in walking speed, change in peak vGRF magnitude, change in quadriceps strength, and change in knee flexion at initial contact were positively correlated to change in peak KFM; change in knee flexion angle excursion was negatively correlated to change in peak KFM (Table 3); change in vGRF ($r$ = 0.74) and walking speed ($r$ = 0.68) had the highest significant correlations with change in KFM. No regression assumptions were violated when all variables of interest (Table 2) were entered into the stepwise regression model as potential predictors for fast pace walking. Results from the stepwise regression indicate that 75% of the variance in change in peak KFM was accounted for by change in vGRF (51%), change in knee flexion at initial contact (17%), change in knee flexion excursion (5%) and change in concentric quadriceps strength (3%) (Table 3). The directions of these relationships indicate that an increase in vGRF (B = 8.69; 95%CI 6.68 – 10.70), an increase in knee flexion angle at initial contact (B = 0.15; 95%CI 0.18 – 0.32), an increase in knee flexion excursion (B = 0.10; 95%CI 0.04 – 0.16), and an in increase in concentric quadriceps strength (B = 0.79; 95%CI 0.22 –1.36) were associated with an increase in peak KFM. In descending order of relative strength of contribution to the model, the standardised coefficients indicate, that change in peak GRF (β = 0.62), change in knee flexion angle at initial contact (β = 0.32), change knee flexion excursion (β = 0.23), and change in concentric strength (β = 0.18), contribute to change in peak KFM respectively (Table 3).

There was a positive correlation between change in peak vGRF and (i) change in walking speed and (ii) change in knee flexion angle at initial contact; a negative correlation was found between change in peak vGRF and change in knee excursion angle (Table 4). However, only change in walking speed was significantly associated with change in peak vGRF in the regression models, accounting for 49% of the variance. An increase in walking speed (B = 0.44; 95%CI 0.32 – 0.55) was associated with an increase in peak vGRF (Table 5).

**4.0 DISCUSSION**

Understanding factors related to the increase in peak KFM during gait is potentially meaningful given that a higher peak KFM during gait at 3-months post-APM is related to the subsequent 2-year patellar cartilage volume loss (Hall et al., 2015). The main finding of this study is that an increase in the peak vGRF and change in knee flexion angle explain up to 75% of the change in peak KFM. The increase in the peak vGRF is primarily related to increase in walking speed. Our observations may facilitate the development of interventions that aim to reduce the peak KFM, which potentially might slow the onset or progression of knee osteoarthritis in these patients.

Of the biomechanical variables assessed in this study, the increase in peak vGRF was the primary variable associated with the increase in the peak KFM for both normal and fast pace walking, accounting for more than 50% of the variance. It is well recognised that walking speed can influence KFM and GRF magnitudes (Goldberg and Stanhope, 2013; Kirtley et al., 1985; Lelas et al., 2003; Mundermann et al., 2004; Winter, 1984). Although the average walking speed did not differ between baseline and follow-up assessments for either walking pace, change in walking speed significantly correlated with peak KFM change ($r = 0.68$-$0.69$), and accounted for 59-63% of the change in peak vGRF magnitude. These findings indicate that reducing the increase in walking speed would likely reduce the increase in peak vGRF, and thereby KFM. However, encouraging a slower walking speed is unlikely to be an attractive strategy for middle-aged adults following APM. Furthermore, walking at a slower pace would likely require a greater number of steps for an equal distance. This would theoretically increase the cumulative knee load and possibly attenuate any potential benefit of reducing the peak KFM.

In addition to walking speed, a reduction in knee excursion angle was also significantly associated with an increase in peak vGRF. However, the influence of knee excursion angle is relatively minimal, accounting for only a further 6% of the increase in vGRF. Theoretically, reducing the knee excursion angle could influence control of the vertical acceleration of the body's center of mass during weight acceptance, leading to an increase in peak vGRF. A reduction in knee excursion angle may lead to a more abrupt deceleration of the body's centre of mass, thereby increasing vGRF. Interestingly, in the current study we noted a significant *increase* in knee excursion angle during stance, yet a significant increase in peak vGRF and peak KFM for both walking paces. This indicates that factors other than knee excursion angle during stance have a greater influence on peak GRF, and thus change in peak KFM magnitude.

Along with an increase in vGRF, an increase in knee flexion angle explained change in peak KFM. In particular, an increase in knee flexion angle explained between a further 17-19% of the increase in peak KFM. For normal pace walking, the final regression model indicates that for every 1º increase in peak knee flexion angle during stance, there was an associated increase in peak KFM by 0.15 (95% CI, 0.11 – 0.20, Nm/(BW×HT)%). For fast pace walking, the final regression model indicates that for every 1º increase in knee flexion angle at initial contact there was an associated increase in peak KFM by 0.15 (95% CI, 0.08 – 0.22, Nm/(BW×HT)%). It is unclear why discordant parameters of the knee flexion angle explained change in peak KFM between normal and fast walking pace. Collectively, these findings suggest that by reducing the knee flexion angle by as little as 1º during stance may reduce peak KFM by approximately 4% of the magnitude assessed at 3 months following surgery. However, the amount of peak KFM change required to prevent or delay adverse cartilage change in these patients remains to be investigated. Moreover, the amount of change in knee flexion angle required to reduce the peak KFM by a clinically meaningful amount also remains to be evaluated.

Maximal concentric quadriceps strength also emerged as a significant predictor of increased peak KFM during normal and fast pace walking. However, the relative contribution explaining the increase in peak KFM was minimal, accounting for 2-3%. Therefore, considering the well-accepted benefit of quadriceps strength (Bennell et al., 2013) and risk of knee osteoarthritis associated with knee muscle weakness (Oiestad et al., 2015) we consider it important for middle-aged patients to regain knee muscle strength following APM.

The biomechanical parameters underpinning an increase in KFM in this study could be considered to reflect recovery from surgery. For example, increased walking speed which substantially accounted for increase in vGRF, increased peak knee flexion angle and increased knee extensor strength, may be considered as part of the recovery from surgery as observed following other surgical procedures including anterior cruciate ligament reconstruction (Hart et al., 2010) and total knee replacement (Sosdian et al., 2014). However, consistent with Sturnieks et al., (2008), our data indicate peak KFM during gait in APM patients was comparable to healthy controls at 3 months following surgery (Hall et al., 2013). Importantly, the clinical concern is that a higher peak KFM at 3 months post-APM relates to patellar cartilage loss over the subsequent 2 years (Hall et al., 2015). Furthermore, an increased KFM in combination with larger peak knee flexion angle will increase the patellofemoral contact force (van Eijden et al., 1986), which is likely to be associated with loss of patellofemoral cartilage.  Therefore, of the parameters identified in the current study partially underpinning the change in peak KFM, reducing the peak knee flexion angle during stance is the perhaps the most logical target for an intervention aiming to reduce the increase in peak KFM, and patellofemoral contact force, in these patients. Possible strategies to reduce the increase in peak knee flexion angle might include gait retraining, although the effectiveness of such a strategy on knee flexion kinematics has not been evaluated to date. Alternatively, computational biomechanical models could be employed to induce these same changes to assess the effects on KFM (Donnelly et al., 2012; Fregly et al., 2007).

To our knowledge this is the first study to explore modifiable biomechanical characteristics underpinning increases in peak KFM over time. Although our observations provide insight into the increase in peak KFM following APM, the regression models did not explain 25% of the variance in increase in peak KFM. There are several possible reasons for the unaccounted variance. First, the KFM is quantified using inverse dynamics which incorporate segment accelerations and inertial properties of the lower leg that were not considered in this study. Second, the KFM depends on the sagittal plane GRF, which is not only derived from the vertical GRF but also from the anterior/posterior GRF components. Therefore, alterations in these other GRF components are also likely to partially explain the change of peak KFM over time. Third, as the KFM can be influenced by numerous variations it is possible that individuals adjust their posture and gait patterns in various ways. For example, Winter (1984) demonstrated postural adjustments, such as leaning forward can trade-off between hip and extension moment while maintaining a constant support moment (i.e. if hip extension moments increased the knee extension moment decreases).

This study has limitations. First, only 80% of the cohort was available for analyses as 16 participants did not return for follow-up assessment. However, as there were no differences in study variables between those who completed the study and those who did not, it is unlikely that participant attrition influenced our results. Second, we did not match walking speeds between baseline and follow-up. Although there were no significant differences in walking speed for either normal or fast pace walking between baseline and follow-up, change in walking speed accounted for a substantial proportion of the change in vGRF (59-63%). Nevertheless, walking at a self-selected pace arguably produces more generalisable estimate of the KFM. Third, the absence of information regarding the amount and location of meniscus removed is a limitation as these have been shown to alter joint contact force (Atmaca et al., 2013; Dong et al., 2014), and possibly the peak KFM. Finally, as in any correlation study, the observed associations do not necessarily indicate causation.

In conclusion, an increase in vGRF and knee flexion from 3 months following surgery over the subsequent two years largely accounted for an increase in peak KFM in this sample of APM patients. Although these changes may in part considered to reflect recovery from surgery, peak KFM is comparable in the APM leg of patients compared to controls at baseline. Importantly, APM patients are at increased risk of developing patellofemoral knee osteoarthritis (Englund and Lohmander, 2005) and a higher peak KFM has been implicated in the role of patellar degeneration (Teng et al., 2015; Hall et al., 2015). This study improves our understanding of biomechanical parameters that underpin the increase in peak KFM and may assist with developing interventions aiming to reduce a higher peak KFM in APM patients.

**ACKNOWLEDGEMENTS**

This study was funded by an Australian National Health and Medical Research Council project grant (#NHMRC 334151) and the Western Australian Health and Medical Research Infrastructure Fund. Professor KLB is supported by a NHMRC Principal Research Fellowship and A/Professor RSH is supported by an Australian Research Council Research Future Fellowship (#FT 130100175). The study sponsors did not play any role in the study design, collection, analysis or interpretation of data; nor in the writing of the manuscript or decision to submit the manuscript for publication.

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**Table 1** Summary baseline and follow-up of gait related variables

| | Baseline mean (SD) | Follow-up mean (SD) | Mean difference [a] | 95% CI | P value |
|---|---|---|---|---|---|
| Time of assessment from surgery (mths) | 3.2 (0.5) | 30.0 (2.8) | - | - | - |
| ***Normal pace walking*** | | | | | |
| Walking speed (m/s) | 1.36 (0.15) | 1.37 (0.16) | 0.01 | -0.02 to 0.04 | 0.572 |
| Knee flexion at initial contact (º) | 3.37 (2.97) | 4.31 (3.69) | 0.94 | 0.09 to 1.80 | **0.031** |
| Peak knee flexion (º) | 40.01 (5.04) | 42.80 (4.99) | 2.79 | 1.90 to 3.68 | **<0.001** |
| Knee flexion excursion (º) | 36.65 (5.32) | 38.29 (6.16) | 1.64 | 0.76 to 2.52 | **<0.001** |
| Peak vGRF (BW) | 1.18 (0.09) | 1.20 (0.10) | 0.02 | 0.00 to 0.04 | **0.025** |
| Peak KFM (Nm/(BW×HT)%) | 4.39 (1.41) | 4.98 (1.44) | 0.60 | 0.28 to 0.91 | **<0.001** |
| ***Fast pace walking*** | | | | | |
| Walking speed (m/s) | 1.92 (0.19) | 1.91 (0.21) | -0.01 | -0.05 to 0.04 | 0.806 |
| Knee flexion at initial contact (º) | 6.54 (3.49) | 6.97 (3.77) | 0.43 | -0.44 to 1.30 | 0.327 |
| Peak knee flexion (º) | 37.74 (4.44) | 41.17 (4.35) | 3.43 | 2.47 to 4.38 | **<0.001** |
| Knee flexion excursion (º) | 31.12 (5.20) | 34.13 (5.51) | 3.01 | 1.91 to 4.11 | **<0.001** |
| Peak vGRF (BW) | 1.41 (0.14) | 1.44 (0.14) | 0.03 | 0.00 to 0.07 | **0.027** |
| Peak KFM (Nm/(BW×HT)%) | 6.87 (1.89) | 7.72 (1.65) | 0.85 | 0.43 to 1.27 | **<0.001** |

[a] calculated as follow-up minus baseline

GRF; ground reaction force: KFM; knee flexion moment; BW: body weight; HT: height

**Table 2** Simple linear correlations between change in peak knee flexion moment during normal and fast pace walking and in change in other variables

| ***Independent predictor variable*** | ***r*** | ***p*** |
|---|---|---|
| **Normal pace walking** | | |
| Δ Walking speed (m/s) | 0.69 | <0.001 |
| Δ Body mass (kg) | -0.19 | 0.13 |
| Δ Knee flexion at initial contact (º) | 0.42 | 0.001 |
| Δ Peak knee flexion (º) | 0.29 | 0.02 |
| Δ Knee flexion excursion (º) | -0.19 | 0.13 |
| Δ Peak vGRF (BW) | 0.75 | <0.001 |
| Δ Concentric quadriceps strength (Nm/kg)[¥] | 0.31 | 0.01 |
| Δ Eccentric quadriceps strength (Nm/kg)[¥] | 0.30 | 0.02 |
| **Fast pace walking** | | |
| Δ Walking speed (m/s) | 0.68 | <0.001 |
| Δ Body mass (kg) | -0.12 | 0.36 |
| Δ Knee flexion at initial contact (º) | 0.61 | <0.001 |
| Δ Peak knee flexion (º) | 0.20 | 0.12 |
| Δ Knee flexion excursion (º) | -0.30 | 0.02 |
| Δ Peak vGRF (BW) | 0.74 | <0.001 |
| Δ Concentric quadriceps strength (Nm/kg) | 0.38 | 0.002 |
| Δ Eccentric quadriceps strength (Nm/kg) | 0.33 | 0.01 |

GRF; ground reaction force; KFM: knee flexion moment; BW: body weight; HT: height

[¥]results unchanged when Δ peak KFM normalized in same way as strength (Nm/kg)

**Table 3** Summary of regression outputs for the change in peak knee flexion moment (Nm/(BW×HT)%) for normal and fast pace walking.

| | Variables entered | Standardised coefficients | Unstandardised coefficients | Model summary | | | | |
|---|---|---|---|---|---|---|---|---|
| | | β | B (95% CI) | R | $R^2$ | Adj $R^2$ | $R^2$ Δ | p-value |
| **Model** | **Normal Pace Walking** | | | | | | | |
| 1 | Δ Peak vGRF (BW) | 0.75 | 11.36 (8.83 – 13.90) | 0.75 | 0.56 | 0.55 | | <0.001 |
| 2 | Δ Peak vGRF (BW)<br>Δ Peak knee flexion (°) | 0.83<br>0.44 | 12.57 (10.60 – 14.54)<br>0.16 (0.11 – 0.20) | 0.86 | 0.75 | 0.74 | 0.19 | <0.001 |
| 3 | Δ Peak vGRF (BW)<br>Δ Peak knee flexion (°)<br>Δ Concentric quadriceps (Nm/kg) | 0.80<br>0.43<br>0.13 | 12.16 (10.19 – 14.12)<br>0.15 (0.11 – 0.20)<br>0.44 (0.02 – 0.85) | 0.87 | 0.76[¥] | 0.75 | 0.02 | <0.001 |
| **Model** | **Fast Pace Walking** | | | | | | | |
| 1 | Δ Peak vGRF (BW) | 0.72 | 10.00 (7.52 – 12.48) | 0.72 | 0.52 | 0.51 | | <0.001 |
| 2 | Δ Peak vGRF (BW)<br>Δ Knee flexion at initial contact (°) | 0.59<br>0.43 | 8.16 (6.04 – 10.29)<br>0.21 (0.13 – 0.28) | 0.83 | 0.68[¥] | 0.67 | 0.17 | <0.001 |
| 3 | Δ Peak vGRF (BW)<br>Δ Knee flexion at initial contact (°)<br>Δ Knee flexion excursion (°) | 0.66<br>0.34<br>0.24 | 9.21 (7.13 – 11.29)<br>0.16 (0.09 – 0.23)<br>0.10 (0.04 – 0.17) | 0.86 | 0.73 | 0.72 | 0.05 | 0.002 |
| 4 | Δ Peak vGRF (BW)<br>Δ Knee flexion | 0.62<br>0.32<br>0.23 | 8.69 (6.68 – 10.70)<br>0.15 (0.08 – | 0.87 | 0.76 | 0.75 | 0.03 | 0.007 |

| | | |
|---|---|---|
| at initial contact (º) | 0.18 | 0.22) |
| Δ Knee flexion excursion (º) | | 0.10 (0.04 – 0.16) |
| Δ Concentric quadriceps (Nm/kg) | | 0.79 (0.22 – 1.36) |

vGRF: vertical ground reaction force; BW: body weight
¥results unchanged when Δ peak KFM normalized in same way as strength (Nm/kg)

**Table 4** Simple linear correlations between change in peak vertical ground reaction force magnitude (BW) and change in other variables

| ***Independent predictor variable*** | ***r*** | ***p*** |
|---|---|---|
| **Normal pace walking** | | |
| Δ Walking speed (m/s) | 0.79 | <0.001 |
| Δ Body mass (kg) | -0.29 | 0.02 |
| Δ Knee flexion at initial contact (°) | 0.17 | 0.18 |
| Δ Peak knee flexion (°) | -0.18 | 0.15 |
| Δ Knee flexion excursion | -0.36 | 0.004 |
| **Fast pace walking** | | |
| Δ Walking speed (m/s) | 0.73 | <0.001 |
| Δ Body mass (kg) | -0.19 | 0.13 |
| Δ Knee flexion at initial contact (°) | 0.31 | 0.02 |
| Δ Peak knee flexion (°) | -0.19 | 0.13 |
| Δ Knee flexion excursion | -0.41 | <0.001 |

BW: body weight

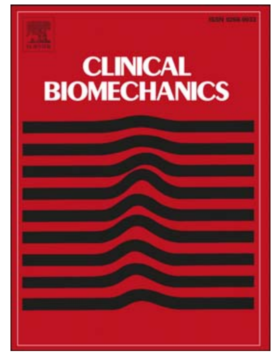
**Table 5** Summary of regression outputs for the change in peak vertical ground reaction force for normal and fast pace walking

| | Variables entered | Standardised coefficients | Unstandardised coefficients | Model summary | | | | |
|---|---|---|---|---|---|---|---|---|
| | | β | B (95% CI) | R | $R^2$ | Adj $R^2$ | $R^2$ Δ | p-value |
| **Model** | **Normal Pace Walking** | | | | | | | |
| 1 | Δ Walking speed (m/s) | 0.79 | 0.49 (0.40 – 0.58) | 0.79 | 0.63 | 0.62 | | <0.001 |
| 2 | Δ Walking speed (m/s)<br>Δ Knee flexion excursion (º) | 0.76<br>-0.26 | 0.47 (0.38 – 0.56)<br>-0.01 (-0.01 – 0.00) | 0.83 | 0.69 | 0.68 | 0.06 | <0.001 |
| **Model** | **Fast Pace Walking** | | | | | | | |
| 1 | Δ Walking speed (m/s) | 0.71 | 0.44 (0.32 – 0.55) | 0.71 | 0.50 | 0.49 | | <0.001 |

**Highlights:**

- Change in vertical ground reaction force associates with change in knee flexion moment.
- Change in knee flexion angle contributes to change in knee flexion moment.
- Change in peak vertical force was mostly due to an increase in walking speed.

## Accepted Manuscript




Mechanisms underpinning the peak knee flexion moment increase over 2-years following arthroscopic partial meniscectomy

Michelle Hall, Tim V. Wrigley, Ben R. Metcalf, Rana S. Hinman, Flavia M. Cicuttini, Alasdair R. Dempsey, Peter M. Mills, David G. Lloyd, Kim L. Bennell

PII: S0268-0033(15)00247-8
DOI: doi: 10.1016/j.clinbiomech.2015.09.006
Reference: JCLB 4041

To appear in: *Clinical Biomechanics*

Received date: 10 April 2015
Accepted date: 8 September 2015