Running Head: Joint loading in people with patellofemoral arthritis

Title: Patellofemoral joint loading during stair ambulation in people with patellofemoral osteoarthritis

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ABSTRACT

Objective: This study primarily aimed to determine whether people with patellofemoral joint osteoarthritis (PFJOA) ascend and descend stairs with different patellofemoral joint loading, knee-joint moments, lower-limb kinematics and muscle forces compared to healthy people.

Methods: Participants with isolated PFJOA (n=17), concurrent PFJOA and tibiofemoral osteoarthritis (OA) (n=13) and age-matched controls (n=21) were recruited. Joint kinematics and ground reaction forces were measured while participants ascended and descended stairs at a self-selected speed. Musculoskeletal computer modeling was used to determine lower-limb muscle forces and the patellofemoral joint reaction force (PFJRF), and these parameters were compared between groups with Analyses of Variance tests.

Results: Participants with OA (isolated PFJOA or concurrent PFJOA and tibiofemoral OA) displayed lower knee-extension moments (ascent: \( p=0.001 \); descent: \( p=0.002 \)), lower quadriceps muscle forces (ascent: \( p<0.001 \); descent: \( p=0.004 \)), lower PFJRFs (ascent: \( p<0.001 \); descent: \( p=0.001 \)), and increased anterior pelvic tilt (ascent: \( p<0.001 \); descent: \( p=0.001 \)) than their healthy counterparts. Participants with OA also ascended stairs with increased hip flexion angles (\( p=0.004 \)), while they descended stairs with smaller knee flexion angles (\( p=0.003 \)) and hip abductor muscle forces (\( p=0.001 \)). No differences were evident between the two OA groups.

Conclusion: Compared to healthy counterparts, people with PFJOA (with or without concurrent tibiofemoral OA) displayed lower PFJRFs during stair ambulation, in conjunction with lower knee-extension moments as well as lower quadriceps and hip abductor muscle forces.
Osteoarthritis (OA) frequently affects the patellofemoral joint (PFJ) (1, 2), and PFJOA has more association with knee pain and stiffness than tibiofemoral joint (TFJ) OA (3, 4). While much is known about the biomechanics of TFJOA, especially the knee adduction moment and its effect on medial compartment loading (5, 6), the same cannot be said for PFJOA (7).

The PFJ and TFJ have different biomechanical characteristics, and so individuals with PFJOA may adopt unique gait modifications. Stair ambulation exposes the PFJ to high loads (8), while pain and difficulties with negotiating steps are hallmark features of PFJ disorders (9). Therefore, people with PFJOA may demonstrate joint loading impairments during stair ambulation.

The biomechanics of stair ambulation has been studied in individuals with TFJOA (10, 11). Individuals with more severe TFJOA (Kellgren/Lawrence (K/L) grade 3 or 4) exhibited greater trunk flexion and a lower internal knee extension moment than controls during stair ascent (10), indicating an endeavor to reduce knee joint loading. However, those with less severe TFJOA (K/L grade 1 or 2) did not differ from controls. In contrast, Kaufman and colleagues observed lower knee extension moments in individuals with mild TFJOA (K/L grade 2) than controls during stair ascent and descent (11). Considering that stair ambulation also loads the PFJ, it is likely that individuals with PFJOA, with or without concurrent mild TFJOA, exhibit biomechanical alterations during stair ambulation.

Quantification of PFJ loading can be determined from the PFJ reaction force (PFJRF), which is the compressive force acting between the patella and femoral trochlea. The PFJRF magnitude is primarily influenced by the knee flexion angle and the magnitude of the quadriceps muscle force (12). Attempts to minimize the PFJRF involve alterations to one or both of these quantities. While lower quadriceps strength and smaller vasti muscle volume are features of people with PFJOA (13, 14), our recent study reported no difference in peak
vasti forces between individuals with and without PFJOA during level walking (15). Instead, peak muscle forces for gluteus medius and gluteus minimus were lower, suggesting that hip abductor muscle dysfunction may be a characteristic feature of PFJOA. This finding supports reports of hip abductor dysfunction in younger individuals with PFJ pain (16). Given that ascending and descending stairs are more physically challenging than level walking, it is possible that differences in muscle forces, and therefore PFJ loading, become more evident during stair ambulation for individuals with PFJOA.

The primary aim of this study was to compare lower-limb joint kinematics, knee-joint moments, lower-limb muscle forces, and PFJRFs between individuals with isolated PFJOA, concurrent PFJOA and TFJOA, and no OA. Secondary aims were to: (a) identify potential contributors to the PFJRF; and (b) explore the relationship between PFJRF and patient reported outcomes (e.g., pain, stiffness, function). We hypothesized that during stair ambulation, individuals with PFJOA would exhibit smaller knee flexion angles, lower quadriceps and hip muscle forces, and lower PFJRFs when compared to their healthy counterparts.
PATIENTS AND METHODS

Participants

Thirty participants with PFJOA (17 with isolated PFJOA and 13 with concurrent PFJOA and TFJOA, hereafter referred to as combined OA) and 21 aged-matched controls with no lower-limb joint pain were recruited from the community and provided written consent (Table 1). Participants with PFJOA represented a sample from a randomized controlled trial (17). Inclusion criteria for PFJOA groups included: (i) age ≥40 years; (ii) anterior- or retro-patellar pain severity ≥4 on an 11 point numerical pain scale during at least two activities that load the PFJ (e.g., stair ambulation, squatting); (iii) pain during these activities on most days of the previous month; and (iv) K/L grading of the PFJ >1 (9). Exclusion criteria included: (i) body mass index (BMI) >35 kg.m$^{-2}$; (ii) concomitant pain from other knee structures, hips or lumbar spine; (iii) previous lower-limb arthroplasty or osteotomy; (iv) recent knee injections (within 3 months of study commencement); (v) moderate to severe TFJOA (K/L grade >2 on a posteroanterior radiograph (9); and (vi) inability to understand written or spoken English.

All participants with OA fulfilled the combined clinical and radiographic American College of Rheumatology (ACR) criteria for the diagnosis of knee OA (knee pain, stiffness ≤30 mins and osteophytes on x-ray) (18). No participants in the control group fulfilled these criteria. Ethical approval was obtained from The University of Melbourne Human Research Ethics Committee prior to commencement, and all human testing procedures undertaken conformed to the standards of the Declaration of Helsinki.

Clinical assessment

Radiographic TFJOA severity was assessed by two investigators (KMC and RSH) using the K/L grading system from a semi-flexed, postero-anterior weight-bearing short film view (19). Radiographic PFJOA severity was assessed from weight-bearing skyline radiographs using...
the K/L grading system adapted to the PFJ (9). Participants in the isolated PFJOA group had a K/L grade of ≥1 for the PFJ and a K/L grade of ≤1 for the TFJ in the same knee, whereas participants in the combined OA group had a K/L grade of ≥1 for the PFJ and a K/L grade of 2 for the TFJ in the same knee. The inter-rater reliability for grading radiographic OA was acceptable (κ = 0.745-0.843) (15).

**Knee osteoarthritis symptoms**

The Knee Injury and Osteoarthritis Outcome Score (KOOS) is a reliable patient-reported outcome measure (20, 21) that comprises of five subscales: pain, symptoms, function in daily activities (ADL), function in sport and recreation (Sport/Rec), and knee-related quality of life (QoL). A normalized score between 0 (maximum symptoms) and 100 (no symptoms) was calculated for each subscale.

**Gait experiments**

Quantitative gait analysis during stair ambulation took place in the Biomotion Laboratory at The University of Melbourne. Details of the experimental protocol have been described previously (15). Reflective markers were placed at specific anatomical landmarks on the trunk, pelvis, and upper- and lower-limbs. Marker trajectories were captured from nine cameras at 120 Hz (Vicon, Oxford Metrics Ltd, Oxford, UK), while ground reaction force (GRF) data were recorded simultaneously at 1080 Hz from a ground-embedded force plate and two portable AccuGait force plates (AMTI, Massachusetts, USA) mounted in a custom-built staircase. Marker and GRF data were low-pass filtered at 4 and 60 Hz, respectively, using a fourth-order Butterworth filter. Muscle electromyographic (EMG) activity were collected at 1080 Hz with pairs of Ag/AgCl surface electrodes (MediMax Global, Shalden, Hampshire, UK) mounted over gluteus maximus, gluteus medius, vastus lateralis, and soleus. An initial static trial was performed with the participant standing in a neutral pose.
Participants subsequently ascended and descended a flight of three steps (step height of 16.5 cm) wearing standardized footwear at a self-selected speed (calculated from the average horizontal velocity of the posterior pelvis marker). All participants ascended and descended stairs without aids (e.g., handrails or canes).

**Lower-limb muscle forces and PFJ loading**

A generic, three-dimensional, musculoskeletal model was implemented in OpenSim (22), an open-source musculoskeletal modeling software program, to calculate lower-limb joint kinematics, joint moments and muscle forces. The skeleton was represented as a 12-segment, 31-degree-of-freedom mechanical linkage, actuated by 92 muscle-tendon units. Each muscle-tendon unit was modeled as a three-element Hill-type muscle, which takes into account the physiological force-length-velocity properties of muscle, in series with an elastic tendon (23, 24). The full body model has been reported previously (25). Participant-specific musculoskeletal models were generated by scaling the generic model based on body-segment dimensions collected from the static trial (22).

For each participant, a representative trial for stair ascent and descent was chosen arbitrarily from a group of successful trials. A successful trial was one with valid foot contacts on all force plates and no missing force plate or marker data. Joint angles were computed using an inverse kinematics analysis that minimized the sum of the squared differences between the positions of virtual markers on the model and the experimental markers (26). Internal joint moments were calculated using an inverse dynamics approach, and muscle forces were computed using a static optimization algorithm (27). The static optimization solution was constrained to the force-length-velocity properties of each muscle (24, 27). Lower-limb muscle forces of interest were: (1) gluteus maximus; (2) hip abductors (gluteus medius and gluteus minimus); (3) quadriceps (vastus lateralis, intermedius, medialis, and rectus femoris);
and (4) ankle plantarflexors (soleus and gastrocnemius). The temporal validity of the predicted muscle forces was evaluated against EMG onset and offset times.

The PFJRF was determined using a separate empirically-based model of the PFJ (12), and calculated using the following equation:

$$PFJRF = \sqrt{F_q^2 + F_p^2 - 2F_qF_p \cos \beta}$$  \hspace{1cm} (1)$$

where $F_q$ is the quadriceps force, $F_p$ is the patellar tendon force, and $\beta$ is the angle between the quadriceps muscle and patellar tendon (patellar mechanism angle). The patellar tendon force and patellar mechanism angle were calculated using data from an in vitro study (12). Based on these data, empirical equations were established for: (a) the patellar mechanism angle as a function of knee flexion angle; and (b) patellar tendon force-to-quadriceps force ratio as a function knee flexion angle (12). Quadriceps force and knee flexion angle calculated from the musculoskeletal model were applied to these empirical equations to determine the patellar tendon force and patellar mechanism angle, which were then used in Eq. (1) to calculate the PFJRF.

Data management and statistical analyses

Data were analyzed for the most affected limb for the OA groups and a randomly chosen limb for the control group. Data were time-normalized to the stance phase and averaged across all participants for each group. The computed PFJRF, lower-limb muscle forces and GRF were normalized to body weight, while joint moments were normalized to body weight multiplied by height. Variables of interest were taken at the time of contralateral toe-off (CTO) for statistical analysis, since peak knee extension moment closely coincides with this time-point during stair ambulation (28-30) and because biomechanical differences between
healthy and pathological individuals have been observed around CTO for stair ambulation (30).

Participant characteristics were compared with the One-way Analysis of Variance (ANOVA) or chi-square ($\chi^2$), as appropriate. An ANOVA was used to determine group differences in dependent variables (PFJRF, lower-limb muscle forces, sagittal-plane joint kinematics and knee-joint moments) during stair ascent and descent. Age was the only participant characteristic to significantly correlate with PFJRF during stair descent ($r=-0.414; p=0.023$); thus, between-group comparisons for PFJRF were conducted with and without age as a covariate (ANCOVA). Post-hoc comparisons involving the Least Significant Difference (LSD) test were used to determine between-group differences, where appropriate. Significance was set at $\alpha<0.05$. The contributions of the GRF magnitude and moment arm (defined as the perpendicular sagittal-plane distance from the GRF line-of-action to the knee joint centre) to the PFJRF were evaluated using forward stepwise multiple regression analyses. The relationships between PFJRF and the subscales of the KOOS were evaluated in the OA participants with Pearson’s correlation coefficients. Relationships were defined a priori: $>0.75$ as good to excellent; $0.50-0.75$ as moderate to good; and $0.25-0.50$ as fair (31).
RESULTS

Participant characteristics

There were no differences in age, gender, height, weight or stair ambulation speed between groups (Table 1). Participants in the OA groups exhibited greater radiographic disease severity than those in the control group.

Stair ascent

Group differences were observed for pelvic tilt and hip flexion angles (Table 2; Figure 1). Participants with isolated PFJOA ascended stairs with greater anterior pelvic tilt (mean difference 4.1° [95% confidence interval 1.6 to 6.7]; p=0.002) and hip flexion (4.6° [0.7 to 8.5]; p=0.023) than controls. Similarly, those with combined OA ascended stairs with greater anterior pelvic tilt (6.9° [4.1 to 9.7]; p<0.001) and hip flexion (7.1° [2.8 to 11.3]; p=0.002) than controls. No significant differences were observed between the isolated PFJOA and combined OA groups for pelvic and hip kinematics. There were no group differences for trunk flexion, knee flexion or ankle dorsiflexion.

Group differences were observed for the knee extension moment (Table 2; Figure 2). The isolated PFJOA and combined OA groups ascended stairs with a knee extension moment that was 29% (-1.56%BW·Ht [-2.38 to -0.74]; p<0.001) and 44% (-2.38%BW·Ht [-3.27 to -1.49]; p<0.001) lower, respectively, than the control group. No significant differences in knee extension moment were found between OA groups.

Group differences were observed for quadriceps muscle forces (Table 2; Figure 3). Compared to the control group, the isolated PFJOA group displayed a 26% lower quadriceps force (-0.65 BW [-0.99 to -0.31]; p<0.001), whereas the combined OA group displayed a 35% lower quadriceps force (-0.86 BW [-1.16 to -0.53]; p<0.001). There were no significant differences
in quadriceps forces between OA groups. No between-group differences were observed for gluteus maximus, hip abductor or ankle plantarflexor muscle forces.

During stair ascent, the mean [95% CI] PFJRF for the isolated PFJOA (1.61 BW [1.41 to 1.81]) and combined OA groups (1.50 BW [1.28 to 1.73]) were significantly lower than the control group (2.15 BW [1.97 to 2.33]), (p<0.001) (Figure 2). The PFJRF was 25% lower for the isolated PFJOA group (-0.54 BW [-0.81 to -0.28]; p<0.001) and 30% lower for the combined OA group (-0.65 BW [-0.94 to -0.37]; p<0.001). No significant differences in the PFJRF were evident between OA groups.

**Stair descent**

Group differences were observed during stair descent for pelvic tilt and knee flexion angles (Table 2; Figure 1). Anterior pelvic tilt was significantly higher during stair descent for participants with isolated PFJOA (3.7° [1.0 to 6.5]; p=0.009) and combined OA (5.9° [2.9 to 8.9]; p<0.001) compared to controls. Participants with isolated PFJOA displayed a more extended knee compared to controls (7.7° [3.5 to 11.9]; p=0.001). Such differences were not found for participants with combined OA (p=0.068). No differences in pelvic or knee kinematics were observed between OA groups. Furthermore, trunk flexion, hip flexion and ankle dorsiflexion angles were not significantly different between groups.

Group differences were observed for the knee extension moment during stair descent (Table 2; Figure 2). Compared to controls, the isolated PFJOA and combined OA groups descended stairs with a knee extension moment that was lower by 51% (-2.78%BW-Ht [-4.30 to -1.27]; p<0.001) and 38% (-2.04%BW-Ht [-3.68 to -0.41]; p=0.016), respectively, with no significant difference evident between OA groups.
Participants with PFJOA descended stairs with significantly lower quadriceps and hip abductor muscle forces than controls (Table 2; Figure 3). Specifically, the isolated PFJOA group demonstrated a 32% lower quadriceps force (-0.94 BW [-1.52 to -0.37]; \( p = 0.002 \)) and a 27% lower hip abductor force (-0.47 BW [-0.81 to -0.14]; \( p = 0.006 \)) compared to the control group. Similarly, the combined OA group showed a 42% smaller quadriceps force (-0.77 BW [-1.40 to -0.16]; \( p = 0.015 \)) and a 35% smaller hip abductor force (-0.63 BW [-0.99 to -0.28]; \( p = 0.001 \)) compared to the control group, with no significant differences evident between OA groups. No between-group differences were observed for gluteus maximus or ankle plantarflexor muscle forces.

The PFJRF was significantly different \( (p = 0.001) \) between the control group (1.72 BW [1.43 to 2.01]), isolated PFJOA group (0.92 BW [0.59 to 1.24]) and combined OA group (1.12 BW [0.74 to 1.49]) (Figure 2). Participants with isolated PFJOA descended stairs with a 47% lower PFJRF (-0.80 BW [-1.24 to -0.37]; \( p = 0.001 \)), whereas those with combined OA descended stairs with a 35% lower PFJRF (-0.60 BW [-1.08 to -0.13]; \( p = 0.013 \)). No significant differences in the PFJRF were observed between OA groups. The results from the ANOVA were no different when age was included as a co-variante \( (p = 0.001) \).

**Predictors of PFJRF**

For stair ascent, the linear regression modeling revealed that GRF magnitude \( (B = 1.845; p < 0.001) \) and GRF moment arm \( (B = -6.784; p = 0.004) \) were strongly associated with the PFJRF \( (r^2 = 0.697; p < 0.001) \). Similarly, for stair descent, the GRF moment arm \( (B = -14.686; p < 0.001) \) and GRF magnitude \( (B = 0.520; p = 0.024) \) were strongly associated with the PFJRF \( (r^2 = 0.822; p < 0.001) \).
Relationship between PFJRF and knee OA symptoms

For the OA participants (n=30), fair correlations were found during stair descent between a higher PFJRF and a higher KOOS-Sport/Rec score ($r=0.483, p=0.007$) and KOOS-ADL score ($r=0.368, p=0.045$). There were no significant associations between the PFJRF and KOOS-pain, KOOS-symptoms or KOOS-QoL. For stair ascent, the PFJRF was not significantly correlated with any of the KOOS subscales.
DISCUSSION

This study investigated lower-limb biomechanics during stair ambulation in individuals with isolated PFJOA, concurrent PFJOA and TFJOA, and no OA. Individuals with PFJOA demonstrated lower knee extension moments, quadriceps forces and PFJRF at CTO during stair ascent and descent than controls, and lower hip abductor forces during stair descent than controls. Both OA groups utilized increased anterior pelvic tilt during stair ascent and descent and increased hip flexion during stair ascent, while those with isolated PFJOA descended stairs with a more extended knee. The findings from this study demonstrate that people with PFJOA have characteristic biomechanical impairments during stair ambulation.

The lower PFJRF observed in both PFJOA groups can be partially explained by the changes in the magnitude of the GRF and its line-of-action with respect to the knee-joint centre, the latter determining the moment arm of the GRF relative to the knee. During stair ascent, participants with PFJOA pushed on the ground less forcefully and utilized movement patterns, such as an increased anterior pelvic tilt angle and greater hip flexion (Figure 1), to shift the body’s centre of mass anteriorly, reducing the moment arm of the GRF at the knee (Figure 4). In contrast to stair ascent, the GRF magnitude contributed less to the PFJRF during stair descent. Primarily, participants with PFJOA reduced the GRF moment arm during stair descent by ambulating with less knee flexion (Figures 1 and 4).

This study expands on current knowledge of stair ambulation in TFJOA and provides unique insights into the pathomechanics of PFJOA. Our finding of a lower knee extension moment confirms earlier observations in individuals with more severe (K/L grade 3 or 4) (10) and mild (K/L grade 2) TFJOA (11). We observed similar findings in both OA groups, including those with isolated, mild radiographic PFJOA. In our study, the severity of TFJOA or PFJOA contributed little to our results, suggesting that differences in gait biomechanics were mostly

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ascribed to the presence or absence of PFJ disease. Given that knee OA frequently involves the PFJ (1, 2), it is possible that the findings from previous knee OA studies are partially attributable to PFJOA. However, the results from this study only provide indirect evidence for this premise, and future research should include an isolated TFJOA group to further understand compartmental-specific gait changes.

Our finding of lower quadriceps force and knee extension moment in both OA groups concurs with the lower quadriceps volume we reported in this cohort (14), and extends on reported findings of weak quadriceps in those with PFJOA (13, 32). Due to the cross-sectional nature of our study, we cannot determine the temporal relationship between PFJOA and lower quadriceps force. However, since stair ambulation results in high PFJRF and is a common source of PFJOA pain (9), it is likely that PFJOA sufferers modulate their stair ambulation mechanics to reduce pain. This possibility is plausible when it is considered that lower quadriceps force was not observed during a less provocative task (i.e., walking) in a larger group of people with PFJOA (15). Furthermore, we did not see differences in knee extension moment, quadriceps force or PFJRF at contralateral foot-strike during stair descent, an instant when adaptations such as modulating knee flexion would be difficult. Experimental pain studies indicate that quadriceps strength (33), activation (34) and knee extension moment (35) are all reduced in the presence of knee pain. However, pain resulted in modest (< 10%) reductions in knee extension moment during level walking (35), indicating that knee pain itself cannot fully explain the differences (29-51%) observed in the current study.

Importantly, while reducing knee extension moment, quadriceps force and PFJRF may be instinctive adaptations to reduce PFJ-related pain, the persistence of such adaptations may result in maladaptive effects, such as lower quadriceps strength and size. Compromised quadriceps function may increase susceptibility to further joint damage over time, through altered sensorimotor function (36), reduced shock absorption (37) and/or joint stiffening.
especially if such impairments eventually become evident in more frequent daily tasks, such as walking. Increased joint stiffness may be associated with the reduced knee flexion observed during stair descent. Such effects can subsequently result in frequent loading of a smaller area of articulation and/or the loading of surfaces that were previously unaccustomed to repetitive loading, with further deterioration of the articular cartilage. As the properties of cartilage and bone may be mechanically conditioned to the type of loading it experiences (38, 39), muscle-atrophy-related changes in cartilage and bone loading could render these structures more vulnerable to injury. Furthermore, there is limited prospective evidence from a cohort study (32) and an animal model (40) to support a causal relationship between lower quadriceps strength and incidence or progression of PFJOA.

Lower hip abductor force was observed in both OA groups during stair descent. This reduction was evident throughout the stance phase of stair descent and may represent a frontal plane adaptation to offload the PFJ and/or the TFJ. Lower hip abductor force is consistent with our findings during level walking in this population (15) and concurs with deficits seen in hip abductor strength in PFJOA (41) and PFJ pain syndrome cohorts (42, 43).

The finding of lower hip abductor force, combined with altered sagittal-plane pelvic kinematics, suggests that the dynamics of the hip joint and pelvis should be considered in the evaluation of people with PFJOA. Further studies may elucidate the temporal relationship between such findings and the development or progression of PFJOA.

Individuals with PFJOA (isolated and combined) exhibited considerable OA symptoms, as evidenced by the mean scores on the KOOS, mostly in the subscales of KOOS-Sport/Rec and KOOS-ADL. Notably, we observed a significant correlation between greater PFJRF at CTO during stair descent and less difficulty in activities of daily living (including stair descent), sports and recreation. Although the strength of this relationship was fair, it appears as though
those that had greater difficulty with functional activities exhibited lower PFJRF during stair descent, possibly due to greater adaptations to offload the PFJ during this task.

Musculoskeletal modeling provides a non-invasive method for determining muscle and joint reaction forces in vivo. The lower-limb muscle and PFJ reaction forces calculated in this study are extensions of the net joint moment calculations, since an infinite combination of muscle forces may contribute to a measured net joint moment. However, as with all modeling approaches, there are several limitations and assumptions that must be acknowledged. Firstly, the muscle-tendon properties in all musculoskeletal models were scaled according to each participant's anthropometry (24) rather than measured directly, which may affect the predictions of muscle forces. Secondly, the static optimization approach used to solve for muscle forces may have limited capacity to predict co-contraction of antagonistic muscles. Hence, the quadriceps muscle forces and PFJRFs may be under-estimated if there was substantial co-contraction between the quadriceps and its antagonists (hamstrings and gastrocnemius) during these activities. Nevertheless, the muscle force predictions in this study were in good temporal agreement with the patterns of EMG activity (Figure 3), and the same scaling approach has been applied successfully in a number of other studies (15, 44-46). Thirdly, the assumption of a planar representation of the PFJ in the PFJ model is a simplification of the true three-dimensional nature of PFJ biomechanics. However, the largest variation in patellofemoral kinematics occurs in the sagittal plane (47), implying that the PFJRF is primarily a sagittal-plane quantity. Furthermore, the PFJRF model incorporated parameters (e.g., the patellar mechanism angle and patellar tendon force-to-quadriceps force ratio) that were based on cadaveric measurements (12). The extent to which these cadaveric measurements accurately represent the biomechanical behavior of the PFJ in vivo is unknown. Nevertheless, our estimations of PFJRF fall within the range of magnitudes calculated in stair ambulation studies (8, 28, 29, 48-50). Furthermore, variations in the patellar mechanism

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angle and the ratio of patellar tendon force-to-quadriceps force of 5% and 10%, respectively, resulted in a change in the PFJRF of no greater than 7.5% for stair ascent and 15% for stair descent at CTO. As such changes are less than the differences found between the control and PFJOA groups, it is unlikely that the main findings were significantly influenced by the use of a model based on cadaveric measurements. It should be noted that a small number (n=5) of the control participants exhibited mild radiographic OA, which may have affected their gait. However, it is challenging to recruit an older cohort of people with no radiographic evidence of OA and none of the control participants reported pain in the knee or other lower-limb joints, which was the primary eligibility criterion. All other participant characteristics were similar between groups. Lastly, the sample size was modest, and future studies should replicate these findings in larger cohorts.

People with isolated PFJOA or concurrent PFJOA and TFJOA ascend and descend stairs with a lower PFJRF when compared to a group of age-matched healthy controls. These reductions were associated with gait modifications, which were activity-dependent. Quadriceps and hip abductor forces were also lower in individuals with OA during stair ambulation, suggesting that hip and knee muscle dysfunction may be characteristics of the PFJOA population. Whilst these modifications may be intuitive adaptations to lower the PFJRF in those with PFJ pain and OA, such changes may not be benign, with potential for long-term deleterious consequences. Further research is required to understand the temporal relationship between gait biomechanical adaptations and the PFJOA disease process.
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FIGURE LEGENDS

**Figure 1.** Mean sagittal-plane joint angles for stair ascent and descent. Results are shown for isolated PFJOA (dotted lines), combined OA (dashed lines), and control participants (solid lines). FS, foot-strike; CTO, contralateral toe-off; CFS, contralateral foot-strike; TO, toe-off.

**Figure 2.** Mean sagittal-plane knee extension moments, ground reaction forces (GRF), moment arms of the GRF calculated about the center of the knee joint, and patellofemoral joint reaction forces calculated for stair ascent and descent. Results are shown for isolated PFJOA (dotted lines), combined OA (dashed lines), and control participants (solid lines).

**Figure 3.** Mean stance-leg muscle forces calculated for stair ascent and descent. Horizontal bars shown below each plot indicate the periods of EMG activity recorded for each muscle group. Results are shown for isolated PFJOA (dotted lines), combined OA (dashed lines), and control participants (solid lines). Glut Max: gluteus maximus; Hip Abduct: gluteus medius and glutus minimus combined; Quad: vastus medialis, vastus intermedius, vastus lateralis and rectus femoris combined; and Ankle Plant: soleus and gastrocnemius combined.

**Figure 4.** Schematic figures showing the body configuration for each group at the time of contralateral toe-off during stair ascent (left) and stair descent (right). Grey, red and blue bodies represent the control, isolated PFJOA, and combined OA participants, respectively. The OA participants are overlaid on the control participant to aid comparison between the groups. The green, red and blue arrows represent the ground reaction force for the control, isolated PFJOA, and combined OA group, respectively. The arms are not shown for clarity. Participants with isolated PFJOA and combined OA ascended stairs by exerting lower ground reaction forces (left panel), and they descended stairs by reducing knee flexion (right panel).
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