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**Title Page**

Sagittal plane joint loading is related to knee flexion in osteoarthritic gait

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**Abstract**

**Background:** High mechanical loading has been consistently linked with medial tibiofemoral osteoarthritis, and is considered to play a central role in the pathogenesis of the disease. Evidence from healthy adults indicates that knee flexion kinematics may influence knee load. The purpose of this study therefore, was to investigate the association between knee flexion kinematics and indicators of joint loading during walking (peak moments and vertical ground reaction force), in individuals with medial tibiofemoral osteoarthritis.

**Methods:** In this cross-sectional study, 89 participants with painful medial tibiofemoral osteoarthritis completed three-dimensional walking gait analysis to measure stance phase ground reaction forces, knee joint moments, and knee flexion kinematics.

**Findings:** In stepwise regression, greater knee flexion excursion was associated with higher peak vertical ground reaction force, accounting for 10% of its variance (B = 0.62 [95% CI 0.34, 0.89], P < 0.001). Greater peak knee flexion was associated with a higher flexion moment, accounting for 44% of its variance (B = 0.12 [95% CI 0.09, 0.15], P < 0.001). No association was found between the knee adduction moment and knee flexion kinematics during walking.

**Interpretation:** Our data suggest that greater knee flexion is associated with higher joint loads in the sagittal plane (i.e. a higher peak knee flexion moment). However, knee flexion kinematics were not associated with the knee adduction moment – a proxy measure of medial compartment knee load. Thus, high knee flexion should be considered an undesirable gait characteristic with respect to knee load in individuals with medial tibiofemoral osteoarthritis.

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## Introduction

Knee osteoarthritis (OA), is a common chronic joint disease that is associated with symptoms of pain and limitations in physical function. Whilst the precise pathophysiology of the disease is not clearly understood, it is typically considered as mechanically driven within the context of systemic susceptability (Andriacchi et al., 2004). In medial tibiofemoral OA, the magnitude of the external knee adduction moment (KAM) is a validated proxy of compartment specific load (Zhao et al., 2007), and is frequently employed to evaluate the role of loading in the disease. Importantly, a higher peak KAM has been associated with more severe radiographic disease (Hurwitz et al., 2002; Sharma et al., 1998) and increased risk of structural deterioration within the medial knee compartment (Bennell et al., 2011; Miyazaki et al., 2002). An understanding of the factors that contribute toward mechanical knee load is required to facilitate the development of strategies to reduce these loads and potentially alter the course of the disease.

Gait patterns associated with knee OA have been broadly described across the literature (Mills et al., In Press). Importantly, some research has identified aspects of gait kinematics that are associated with the KAM and are amenable to change (Simic et al., 2011), such as trunk lean (Hunt et al., 2008; Mundermann et al., 2008) and toe-out (Andrews et al., 1996; Guo et al., 2007; Hurwitz et al., 2002; Jenkyn et al., 2008). It is hypothesised that appropriately modifying these aspects of gait may assist in reducing the KAM and therefore joint loading to potentially retard disease progression. Although research shows that knee OA is associated with altered sagittal plane kinematics, little is known regarding their influence upon indices of

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knee load in people with the disease. Specifically, knee flexion differences are reported at footstrike, with OA patients typically exhibiting greater knee flexion than asymptomatic individuals (Childs et al., 2004; Dixon et al., 2010; Heiden et al., 2009). Contrary to this, OA patients appear to exhibit less peak flexion during midstance than those without OA (Astephen et al., 2008; Smith et al., 2004 ). Thus, knee flexion excursion (the range of knee flexion from footstrike to peak flexion) is consistently reported to be less in individuals with knee OA, compared to asymptomatic individuals (Childs et al., 2004; Dixon et al., 2010; Heiden et al., 2009; Lewek et al., 2006; Rudolph et al., 2007; Schmitt and Rudolph, 2007; Smith et al., 2004). The consequences of these altered kinematics upon joint load are not well understood, and necessitate further investigation.

From a mechanical perspective, altered patterns of knee flexion will have several implications for net joint loads during gait. First, the flexion of the knee that occurs from foot strike through to peak flexion plays an important role in ensuring a gradual deceleration of the vertical velocity of the body's centre of mass. Theoretically, this gradual deceleration will translate to a reduction in the rate of loading and magnitude of the peak vertical ground reaction force (vGRF) that occurs during the first half of stance. Indeed, there is evidence that increased knee flexion translates to attenuated rates of loading and peak vGRF in healthy adults during walking (Riskowski, 2010) and other tasks (Derrick, 2004; Devita and Skelly, 1992; McNitt-Gray et al., 1993, 1994). Observation of a similar response in people with knee OA may have important implications for joint loading. Knee joint moments, an indirect measure of knee load (Schipplein and Andriacchi, 1991; Zhao et al., 2007), are primarily determined by the magnitude of the ground reaction force and its lever arm to the

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knee joint centre (Hunt et al., 2006). Thus, if the magnitude of the peak vGRF the first half of stance is reduced (as a result of greater knee flexion excursion), peak knee moments during the first half of stance may also be lower. Thus, encouraging increased knee flexion may be viewed as an attractive strategy to reduce knee load, and when combined with a medial thrust of the knee this modification to gait has demonstrated success in reducing knee load as quantified by medial compartment contact force (Fregly et al., 2009) and the peak KAM (Fregly et al., 2007).

Contrary to the beneficial effects greater knee flexion excursion may have for joint load via attenuated peak vGRFs, greater knee flexion would likely increase the sagittal plane moment arm length, thus contributing toward a higher knee flexion moment. Recent work indicates that in healthy young females the increase in moment arm length overrides the reduction observed in the magnitude of the vGRF, in that higher flexion moments were observed with increased knee flexion (Riskowski, 2010). The relationship between knee flexion kinematics and knee load during walking in an OA population, however, remains to be established.

The purpose of this study was to examine the role of knee flexion during stance upon the peak vGRF and indicators of knee joint loading in the sagittal and frontal planes during the first half of stance. We hypothesised that greater flexion at foot strike and peak flexion, and greater flexion excursion, would be associated with a lower peak moment acting on the knee in the frontal plane (the KAM), a higher peak moment in the sagittal plane (i.e. the knee flexion moment), and a lower vGRF during the first half of stance.

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## Methods

*Subjects*

Eighty-nine participants with medial compartment knee OA were recruited from the local community as part of a randomised controlled trial (Bennell et al., 2010). All measurements reported here were taken at baseline, prior to any intervention.

Participants with knee OA were included if they were aged >50 years and had knee pain on most days of the previous month (average level >3 on an 11-point numerical rating scale). Other inclusion criteria consisted of: 1) varus malalignment as determined by short-film radiographs, 2) predominance of pain/tenderness over the medial region of the knee, and 3) osteoarthritic changes in the medial compartment of the tibiofemoral joint (osteophytes and/or joint space narrowing). Exclusion criteria included: 1) questionable radiographic knee OA (Kellgren & Lawrence [K&L] scale grade 1 (Kellgren and Lawrence, 1957)); 2) lateral tibiofemoral joint space width less than medial; 3) symptoms originating predominantly from the patellofemoral joint as determined by clinical examination; 4) knee surgery or intraarticular corticosteroid injection within 6 months; 5) current or past (within 4 weeks) oral corticosteroid use; 6) systemic arthritic conditions; 7) history of hip or tibiofemoral/patellofemoral joint replacement or tibial osteotomy; 8) any other muscular, joint, or neurologic condition affecting lower extremity function; and 9) inability to ambulate without a gait aid.

Ethical approval was obtained from the University of Melbourne Human Research Ethics Committee, and from the Department of Human Services Victoria, Radiation Safety Committee. All participants provided written informed consent.

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*Instrumentation & Procedures*

The study limb was defined as that with the more painful knee. Standardized semiflexed posteroanterior knee radiographs for each knee were obtained in barefoot standing. Radiographic severity of tibiofemoral OA was assessed using the K&L scale by an experienced musculoskeletal researcher and physiotherapist (MAH) whose intrarater reliability was 0.84 (linearly incremental weighted kappa statistic). According to this system, disease severity is rated on an ordinal scale from 0 to 4: 0 = normal, 1 = possible osteophytes, 2 = minimal osteophytes and possible joint space narrowing, 3 = moderate osteophytes, some narrowing, and possible sclerosis, and 4 = large osteophytes, definite joint space narrowing, and severe sclerosis (Kellgren and Lawrence, 1957).

Anatomic knee alignment was measured to confirm participant eligibility for the study as per the inclusion criteria, and for inclusion as a covariate due to the established link between anatomic knee alignment and knee joint load (Specogna et al., 2007; Wada et al., 2001). Anatomic knee alignment was measured using the posteroanterior radiographs. Alignment measured in this manner is strongly correlated with the mechanical axis obtained from a long leg radiograph ($r = 0.75$; $P < 0.0001$) (Kraus et al., 2005) and avoids the additional cost and radiation associated with a long leg radiograph. A prediction equation was used for conversion (Kraus et al., 2005). Higher mechanical axis values (> 180 degrees) indicated valgus alignment, while values below 180 degrees corresponded to our definition of lower limb varus alignment required for inclusion in the study.

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All participants performed barefoot walking trials at their self-selected, normal walking speed. Speed was monitored using timing gates to ensure that inter-trial variation was not greater than 10%. Force plate data were collected from two plates at 1080Hz (AMTI, Watertown, MA, USA). Synchronised three-dimensional kinematic data were collected at 120 Hz using a Vicon motion analysis system with eight M2 CMOS cameras (Vicon, Oxford, UK). The standard Vicon Plug-in-Gait lower extremity marker set (Vicon) was used, and additional markers were attached to the medial knee and ankle during a single static standing trial to determine the relative positioning of joint centers. Each participant performed five successful walking trials for each limb (trials where the foot landed within the borders of the force plate) and mean data were used for analyses.

Joint moments were calculated for the study knee using inverse dynamic techniques (Vicon Plug-In-Gait v2) and the peak external moments (KAM and knee flexion moment) during the first half of stance were identified. Peak vGRF for the study knee during the first half of stance was identified from the force plate data. Peak knee joint moments were normalised for body weight and height (Nm/BW*HT%), and the peak vGRF was normalised for body weight (N/BW%). Knee kinematics were computed using a joint coordinate system approach (Grood and Suntay, 1983); flexion at footstrike, peak flexion during stance, and flexion excursion from footstrike to peak flexion were identified for analysis. Walking speed was calculated from the average forward velocity of the pelvis during the stance phase of interest. Test-retest reliability of the kinematic, kinetic and ground reaction force variables reported in this study were established in our lab for a group of 11 participants with medial tibiofemoral OA

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measured twice, 1 week apart, as per the study protocol. Reliability was good to excellent; ICC's (3,5) of 0.78 to 0.99.

*Statistical analysis*

Analyses were performed using SPSS for Windows, Version 19 (IBM Corporation, Armonk, NY, USA). Data were checked for normality prior to analyses. An *a priori* alpha level of 0.05 was set for all analyses. First, Pearson correlation coefficients were used to determine the degree of correlation between knee flexion variables and indicators of loading (peak vGRF, peak KAM, and peak knee flexion moment). Forward stepwise regression models with an alpha level to enter of 0.10 were then used to determine the influence of all knee flexion variables upon the peak vGRF, peak KAM, and peak knee flexion moment. Separate regression analyses were performed for the dependant variables of peak vGRF, peak KAM, and peak knee flexion moment, using the independent variables of walking speed, alignment, knee flexion at footstrike, peak knee flexion, and knee flexion excursion. Data were checked to ensure that the standard assumptions of linear regression were met, that is: (i) an approximately linear relationship between the explanatory variables and the outcome variables; (ii) residuals are normally distributed, and (iii) homoscedastic variance. Collinearity statistics were also checked to ensure no collinearity in the final regression models; a variance inflation factor of greater than 4 was considered to indicate multicollinearity (Peat and Barton, 2008).

**Results**

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Participant characteristics are shown in Table 1. There was a relatively equal distribution across K&L grades and genders. Pearson correlation coefficients indicate that peak flexion and flexion excursion were positively correlated with peak vGRF, but flexion at footstrike was not (Table 2). Knee flexion variables were not significantly correlated with the peak KAM. Flexion at footstrike, peak flexion and flexion excursion were all positively correlated with the peak knee flexion moment.

In stepwise linear regression, walking speed and peak knee flexion excursion were significant predictors of the peak vGRF; in the final regression model they explained 52% of the variance in this parameter ($p < 0.001$; Table 3; Figure 1A). Walking speed accounted for 42% of the variance, and knee flexion excursion accounted for a further 10%. The nature of this relationship was such that faster walking speed and greater flexion excursion were associated with a higher vGRF.

Regarding peak KAM, in stepwise linear regression, knee flexion variables were not predictive; rather only alignment and walking speed remained in the final regression model as significant predictors of peak KAM, accounting for 10% of the variance in this parameter ($p = 0.004$; Table 3). Alignment accounted for 5% of the variance, and walking speed accounted for a further 5%. The nature of this relationship was such that more varus malalignment and faster walking speeds were associated with a higher peak KAM.

Stepwise linear regression indicates that peak knee flexion and alignment were significant predictors of the peak knee flexion moment, with the final regression model explaining 47% of the variance in this parameter ($p < 0.001$; Table 3; Figure

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1B). Peak knee flexion accounted for 44% of the variance, and alignment accounted for a further 3%. The nature of this relationship was such that greater peak flexion and less varus malalignment were associated with a higher flexion moment.

## Discussion

The risk of structural deterioration associated with disease progression in medial knee OA has been linked to higher mechanical loading of the joint during walking (Bennell et al., 2011; Miyazaki et al., 2002). Evidence from asymptomatic populations indicate that altered knee flexion kinematics during gait, specifically increased flexion excursion, may be beneficial in attenuating ground reaction forces (Derrick, 2004; Riskowski, 2010), and thus contribute toward a reduction in knee joint load. In our symptomatic cohort, contrary to our hypothesis, knee flexion kinematics were not associated with the peak KAM during walking, and greater peak knee flexion and flexion excursion were associated with a higher knee flexion moment and vGRF. These data suggest that greater knee flexion, and knee flexion excursion, during stance may place higher sagittal plane loads upon the symptomatic OA knee.

Examination of the relationship between the peak vGRF and knee flexion kinematics indicate that greater peak knee flexion, and knee flexion excursion, were associated with a higher peak vGRF. Moreover, in regression modelling greater knee flexion excursion was associated with a higher peak vGRF. These findings are contrary to our hypothesis, and the findings of work in asymptomatic populations that indicate a reduction in the magnitude of the peak vGRF may be expected with greater knee flexion excursion (Derrick, 2004; Riskowski, 2010). Conceivably, the compromised

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control of the quadriceps muscles in OA patients (Hortobágyi et al., 2004), may limit their ability to smoothly modulate the deceleration of their centre of mass, and this may override any potential benefits of altered flexion kinematics. Greater flexion, and flexion excursion, under these conditions (walking gait with compromised quadriceps control), may in fact expose the lower limb system to greater transient accelerations, thus resulting in the observed positive correlations between flexion and loading in this population.

The KAM is considered to be one of the primary mechanical factors associated with disease progression in medial compartment knee OA (Bennell et al., 2011; Miyazaki et al., 2002). Thus, strategies to reduce this moment are particularly desirable. Our data demonstrate little influence of knee flexion kinematics upon peak KAM, indicating that altered knee flexion kinematics will be of little benefit in reducing the KAM in this population. It was hypothesised that alterations in flexion kinematics may reduce the peak KAM, i.e. greater knee flexion will facilitate a reduction in the magnitude of the vGRF, which in turn contributes toward a reduction in the magnitude of the peak KAM. However, as the peak vGRF was positively, rather than negatively, associated with knee flexion excursion in our cohort, it may be expected that greater flexion excursion would be associated with a higher peak KAM. As our regression data indicate, and consistent with other reports in the literature, varus alignment of the knee (Hurwitz et al., 2002) and walking speed (Mundermann et al., 2004) are factors that are associated with the peak KAM in a medial knee OA cohort, and may override the apparent influence of flexion kinematics on peak KAM. Thus, gait interventions designed to reduce the KAM may be best targeted toward

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redressing the varus malalignment associated with medial knee OA, rather than altering sagittal plane kinematics.

The positive relationship observed in this study between self-selected walking speed and loading characteristics (peak vGRF and peak KAM), is consistent with some earlier work in a knee OA population indicating that 8.9% of the variance in the peak KAM is explained by self-selected walking speed (Mundermann et al., 2004). This supports the suggestion that reducing walking speed may lead to a reduction in the peak KAM. Importantly, this earlier study (Mundermann et al., 2004), also examined the individual relationships between walking speed and peak KAM. Whilst the majority of participants exhibited a positive relationship, some exhibited a negative relationship, indicating that peak KAM was higher at slower walking speeds (Mundermann et al., 2004). Moreover, in a study of healthy individuals and those with moderate to severe knee OA, the peak KAM did not differ with increasing walking speed, although the peak vGRF did (Zeni and Higginson, 2009). Thus, given these conflicting findings regarding the relationship between walking speed and the peak KAM, and that the direction of the relationship between walking speed and peak KAM varies between individuals (Mundermann et al., 2004), reducing walking speed should not necessarily be considered an effective strategy to reduce knee joint loads. Furthermore, as a slower walking speed is predictive of accelerated functional decline in the elderly (Viccaro et al., 2011), the negative implictations of walking more slowly may outweigh the possible benefits of reduced knee load.

Knee flexion kinematics at footstrike, peak flexion and flexion excursion, were all positively correlated with the peak knee flexion moment. Unsurprisingly, peak knee

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flexion was the primary predictor of the peak flexion moment. It is likely that this is a consequence of both the higher peak vGRF we observed with greater peak knee flexion and flexion excursion, and an increase in the external flexion moment arm with increasing knee flexion. This increase in the magnitude of the external knee flexion moment is indicative of a higher internal quadriceps moment. Given this greater force requirement that would be placed upon the typically weak quadriceps muscles of medial knee OA patients (Hinman et al., 2010), the adoption of a gait pattern incorporating increased flexion should be discouraged, and indeed may not be feasible for all. Moreover, a higher knee flexion moment is indicative of greater load upon the patellofemoral joint, and thus greater knee flexion may exacerbate symptoms associated with OA in this compartment – a common collateral pathology to medial tibiofemoral OA (Ledingham et al., 1993).

*Study Limitations*

There are limitations associated with our study. Primarily, this was an observational rather than intervention based study, i.e., we examined the relationship between knee flexion kinematics and knee load, rather than the effect of changing flexion kinematics upon knee load. Our data suggest that changing knee flexion kinematics will not be beneficial in reducing frontal plane joint kinetics, but do not prove this. Second, our findings are limited to individuals with established medial compartment knee OA, that are known to demonstrate distinctly different kinematics from other populations (Childs et al., 2004; Rudolph et al., 2007). The influence of flexion kinematics upon knee load may differ in other populations likely to benefit from reduced knee load, such as those with lateral tibiofemoral or patellofemoral OA, or those at risk of developing OA (Riskowski, 2010).

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## Conclusions

In conclusion, whilst data from asymptomatic populations suggest that increased knee flexion may aid in attenuating knee loads, our data indicate that greater knee flexion, and flexion excursion, are associated with higher sagittal plane loads on the OA knee during walking. Reducing knee flexion may be beneficial in lowering the peak vGRF and knee flexion moment, but appears to have little effect on the moment primarily implicated in the pathogenesis of medial knee OA – the KAM.

## Conflict of Interest Statement

The authors declare that they do not have any conflict of interest relating to this paper.

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**Figure Captions**

**Figure 1.** Scatterplots describing the relationships between knee flexion kinematics and knee joint loads during walking. Part A: the relationship between knee flexion excursion and peak vGRF. Part B: the relationship between peak knee flexion angle and peak knee flexion moment.

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**Table 1.** Summary of participant characteristics.

| | **Mean (SD)** |
|---|---|
| **Age (years)** | 64.6 (8.3) |
| **Height (m)** | 1.67 (0.09) |
| **Mass (kg)** | 78.2 (15.8) |
| **BMI (kg/m²)** | 27.9 (4.4) |
| **Sex (n (%))** | |
| Male | 46 (51.7) |
| Female | 43 (48.3) |
| **Pain (/20)*** | 7.3 (3.1) |
| **Disease severity † (n (%))** | |
| Grade 2 | 30 (33.7) |
| Grade 3 | 29 (32.6) |
| Grade 4 | 30 (33.7) |
| **Mechanical Alignment (°)** | 176.8 (2.5) |
| **Walking speed ($ms^{-1}$)** | 1.22 (0.17) |

* Pain scores were reported on the Western Ontario McMaster Universities Osteoarthritis Index. † indicates Kellgren and Lawrence disease severity of the study limb.

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**Table 2.** Correlation coefficients describing the univariate association between predictor variables and outcome variables.

| | | **Outcome variables** | |
|---|---|---|---|
| **Predictor variables** | **Peak vGRF (N/BW%)** | **Peak KAM (Nm/BW*HT%)** | **Peak knee flexion moment (Nm/BW*HT%)** |
| **Knee flexion at footstrike (°)** | 0.00 | 0.00 | 0.52* |
| **Peak knee flexion (°)** | 0.32* | 0.09 | 0.67* |
| **Knee flexion excursion (°)** | 0.51* | 0.14 | 0.41* |

* $P < 0.05$.

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**Table 3.** Regression coefficients obtained from regression analyses with indices of joint loading (peak vertical ground reaction force, peak knee adduction moment and peak knee flexion moment) as the dependant variables.

| Variable | B | SE B | 95% CI | β | $R^2$ change |
|---|---|---|---|---|---|
| **Peak vertical ground reaction force** | | | | | |
| Walking speed | 23.70 | 3.38 | 16.99, 30.41 | 0.545 | 0.415 |
| Knee flexion excursion | 0.62 | 0.14 | 0.34, 0.89 | 0.345 | 0.104 |
| **Peak knee adduction moment** | | | | | |
| Alignment | -0.11 | 0.04 | -0.19, -0.03 | -0.276 | 0.049 |
| Walking speed | 1.38 | 0.57 | 0.24, 2.51 | 0.246 | 0.050 |
| **Peak knee flexion moment** | | | | | |
| Peak knee flexion | 0.12 | 0.01 | 0.09, 0.15 | 0.675 | 0.441 |
| Alignment | 0.09 | 0.04 | 0.02, 0.17 | 0.190 | 0.031 |

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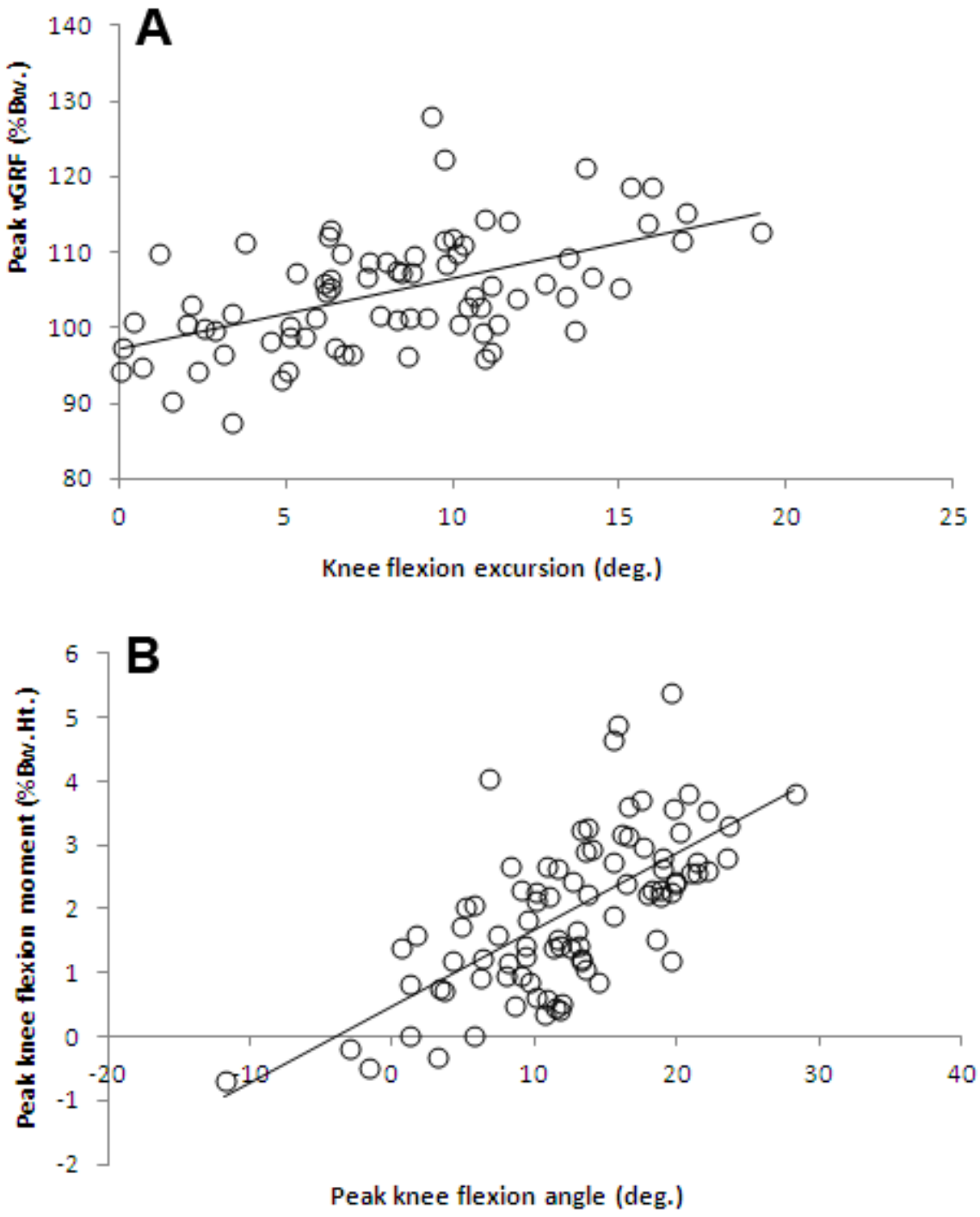



Figure 1