197 **Do sex differences in patellofemoral joint geometry**
198 **influence quadriceps forces? What are the therapeutic**
199 **implications?**

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207 **Abstract**

208 It is widely suggested that women are more at risk of certain types of knee injury. This has
209 prompted a search for sex differences that might explain this increased risk profile. One area
210 that has not received adequate attention is the potential for sex differences in patellofemoral
211 joint geometry. This is notable because even small differences in patellofemoral joint
212 geometry can result in relatively large differences in quadriceps forces. In this paper I review
213 what is known about sex differences in patellofemoral geometry and analyse how such
214 differences might change the loading of the knee. Finally, I indicate how some aspects of
215 patellofemoral geometry might be altered by exercise or therapeutic interventions.

216 Keywords: knee; tibiofemoral joint; patella; anterior cruciate ligament injury; knee
217 osteoarthritis; knee pain

218 **Introduction**

219 Women appear to be more at risk of some types of knee injury, particularly during some
220 sporting activities and tasks (1–3), and osteoarthritis of the knee may be more prevalent in

women (4). For this reason, it has been common for researchers to seek sex-specific differences that might increase female knee injury risk. One factor that is sometimes proposed is that women may be more “quadriceps dominant” than men, and that this would create differences in the loading of the knee. The purpose of this paper is to consider what is known about sex differences in the geometry of the patellofemoral joint (PFJ) in order to establish if PFJ geometry might influence quadriceps forces during movement.

Are there sex differences in sagittal plane PFJ geometry?

One important characteristic of the extensor mechanism of the knee is the fact that the orientation of the patella tendon relative to the tibia (patella tendon angle; π) changes as the tibiofemoral joint (TFJ) flexes (5,6). Of particular significance is the fact that from 0° to around 75° of TFJ flexion (κ) the patella tendon exerts an anterior pull on the tibia, that diminishes as the knee flexes, such that at deeper angles the direction of pull is directed posteriorly (Figure 1). Clearly the nature of this relationship is of great significance to the loading of the structures of the knee during movement. For instance, the tendency of the patella tendon to load the ACL will be greatest when the knee is extended, and this decreases as the knee flexes. This in turn means that individual variations in this relationship are likely to be important in understanding ACL injury risk. There is some consistent evidence that suggests that π is larger in women at all tibiofemoral joint flexion angles (Figure 2). For this reason, this is clearly a factor that could contribute to the higher incidence of ACL injuries experienced by women.

Figure 1. Rotation of the tibia by the patella tendon and cruciate ligaments in A) full tibiofemoral extension and B) deeper tibiofemoral flexion (TFJ = tibiofemoral joint reaction force; ACL = anterior cruciate ligament; PCL = posterior cruciate ligament; PT = patella tendon).

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Figure 2. Sex specific patella parameters taken from Varadarajan et al. (7) and Nunley et al. (8).

248

249 Another well established characteristic of the patellofemoral joint is that the patella functions
250 as a lever, and not, as previously thought, as a smooth pulley (9). In particular, the position
251 of the patella's pivot point on the femur changes as the tibiofemoral joint flexes in order to
252 maintain its force and moment equilibrium (10,11) (Figure 3). This behaviour produces a
253 marked change in the ratio of patella tendon to quadriceps tendon force (12) (P/Q ratio)
254 which varies from above 1:1 at full extension to close to 0.5:1 at a knee flexion angle of
255 around 90 degrees. The effect of this is profound – almost double the quadriceps force is
256 required to create the same force in the patella tendon when the tibiofemoral joint (TFJ) is
257 flexed, as compared to when the TFJ is extended. Despite the fact that the existence of the
258 P/Q ratio is very well established, and has the potential to have a large influence on PFJ and
259 TFJ contact forces, there is a dearth of literature that has sought to quantify sex differences in
260 the relationship. To my knowledge, only one study has compared male and female P/Q
261 ratios, and reported that there was no statistically significant difference (13). In that study,
262 the larger patella tendon angle (π), which can be inferred from the larger patella moment arm,
263 was compensated by a larger quadriceps moment arm, resulting in similar P/Q ratios.
264 However, male and female ratios were not reported separately.

Figure 3. Patellofemoral joint geometry (P = patella tendon line of action; Q = quadriceps tendon line of action; α = angle of incidence of the patella tendon on the patella; β = angle of incidence of the quadriceps tendon on the patella; π = patella tendon angle relative to the tibia; μ = quadriceps tendon angle relative to the femur; ρ = flexion of the patella relative to the femur; κ = tibiofemoral flexion angle). The x-ray image is the work of Nevit Dilman and is reproduced in its adapted version under the terms of its Creative Commons Attribution-ShareAlike 3.0 Unported licence (<https://creativecommons.org/licenses/by-sa/3.0/legalcode>).

As shown in Figure 3, the P/Q ratio can be calculated from the angles of incidence of the patella tendon (β) and the quadriceps tendon (α) on the patella. These two angles are, in turn, a function of the patella tendon angle relative to the tibia (π), the quadriceps angle relative to the femur (μ), the flexion of the patella relative to the femur (ρ), and the tibiofemoral flexion angle (κ). A common modelling assumption is that π , μ , and ρ , are all dependent on κ which means that P/Q ratio can be expressed as a function of κ . We have already seen that there is some literature that suggests that π is generally larger for women than men. In contrast, it is harder to establish if there are sex differences in μ and ρ . With regards to patella flexion angle (ρ), Varadarajan et al. (7) reported that there were no significant differences between men and women (Figure 2). The same was true in Seisler and Sheehan (14), although in this study the average absolute difference was 2.5° smaller in women. In contrast, it seems likely

that the quadriceps tendon angle relative to the femur (μ) is greater for women than men; if the P/Q ratios and patella flexion angles between men and women are similar, this means that μ must be greater in order to compensate for the greater π in women. In support of this contention, there is some evidence that the resultant quadriceps force vector is directed more posteriorly in women (15).

Figure 4 presents a comparison of male and female P/Q ratios calculated from a simple geometrical model that we have presented previously (16,17). In this case, the sex-specific parameters π and ρ are taken from the study of Varadarajan and colleagues (7). The left hand graph is calculated based upon sex-specific values of ρ whereas in the right hand graph the men's values for ρ are used for both men and women. The P/Q ratios displayed on the right hand graph therefore represent the differences created by the difference in patella tendon angle only. The graphs also present the sensitivity of the female P/Q ratios to differences in the quadriceps tendon angle (μ) - in the base case μ is set to the men's value. What Figure 4 demonstrates is that, although the P/Q ratios are qualitatively pretty similar, there are some potential differences. For instance, considering the left hand graph and comparing the male curve to the female base case, at 30° of TFJ flexion, the male P/Q ratio is 0.98, whereas the female ratio is 1.02. This would mean that women can produce the same patella tendon force using 4% less quadriceps force. In contrast, comparing the male curve to the female case with $\mu = +4^\circ$, shows that at 80° of TFJ flexion, women would need to exert an 8% greater quadriceps force to produce the same patella tendon force. What these calculations demonstrate is that even small differences in the PFJ geometry can result in relatively large differences in the relative loading of the patella and quadriceps tendons, with concomitant effects on the PFJ and TFJ loading.

Figure 4. Patella to quadriceps tendon force ratio (ρ) as a function of tibiofemoral joint angle (κ).

In summary, there is evidence that women have a larger sagittal plane patella tendon angle. The existence of sex differences in patella flexion angle, sagittal plane quadriceps tendon angle or P/Q ratio is harder to establish. However, only modest sex differences in PFJ geometry could produce meaningful differences in P/Q ratios and, in turn, quadriceps forces.

Are there sex differences in frontal plane PFJ geometry?

Probably the most widely known sex difference in PFJ geometry is the difference in Q angle. Q angle is an attempt to quantify the direction of pull of the quadriceps tendon on the patella in the frontal plane, and is often defined to be the angle of incidence of the quadriceps tendon on the patella, relative to the line of action of the patella tendon (Figure 5). Although it is widely “understood” that women have greater Q angles due to their wider pelvises, this has been contested (18). In contrast, it has also been shown that there are sex differences in the frontal plane angle of the patella tendon (7) (σ ; Figure 5). In particular, women have a greater frontal plane angle, which will result in the patella tendon exerting a greater lateral pull on the patella. This is in the same direction as the lateral pull which would be a result of a greater Q angle.

Figure 5. Sex differences in frontal plane patella tendon angle (σ) taken from Varadarajan et al. (7). The image of the lower limb has been adapted from an OpenStax diagram (<http://cnx.org/content/col11496/1.6/>) and is reproduced here under the terms of its Creative Commons Attribution-ShareAlike 4.0 International licence (<https://creativecommons.org/licenses/by-sa/4.0/legalcode>).

Most of the attention that has been directed at sex differences in the frontal plane has considered the impact on patella tracking, and in particular whether greater lateral forces or moments are exerted upon the patella. However, there is a further implication. If the frontal plane patella tendon angle (σ) is greater, then a larger proportion of the force acting on the tibia is directed laterally, and a smaller proportion is directed anteriorly. As it is the anterior component of the frontal plane force that extends the tibia, this means that, all things being equal, a larger σ will require a greater quadriceps force to produce a given extension moment. There is some evidence that supports this contention. For instance, Lee (19) found that there

is a correlation between activation of the laterally orientated quadriceps (rectus femoris and vastus lateralis) and the Q angle. In addition, it has been shown in vitro that increasing the Q angle increases the lateral force acting on the patella (20) and that vastus lateralis and medialis forces are correlated in a way that minimises the mediolateral force acting on the patella (21).

In summary, there appear to be sex differences in patellofemoral geometry in the frontal plane. These differences could require women to display larger quadriceps forces for some tasks.

Do women exhibit greater quadriceps forces during movement?

In answering the question as to whether women exhibit greater quadriceps forces during movement, it is important to distinguish between sex and gender differences. In particular, when considering movement, one reason for a difference in quadriceps activation could be that there are differences in movement strategy. This might have little to do with a person's sex, and be more influenced by their familiarity with the task. Thus, if there are differences between men and women, it might simply be that societal expectations as to their behaviour (e.g. physical activity levels, choice of sport, aesthetics of movement) influence their likelihood of having perfected the task (gender differences). Alternatively, there might be inherent anatomical and physiological differences (sex differences) that either cause the greater level of quadriceps activation or influence the movement strategy. For instance, it is frequently reported that women exhibit higher quadriceps forces during athletic movements like landing or cutting (change of direction) (22–24). However, these are often shown to be coincident with other differences in mechanics/movement strategy that might explain the difference. For instance, during landing women are thought to be more prone to landing in a valgus position (25–27).

Clearly, for the purposes of this paper, we are interested in establishing if there are sex differences in quadriceps activation that are independent of movement strategy, and that might be inferred to be a result of the potential sex differences in PFJ geometry (27). Of course, this is challenging, but there is some preliminary evidence of note. In particular, we recently analysed male and female landings where the participants were matched based upon whether they exhibited a medially or laterally loaded TFJ during the landing (28,29). When compared in this way, some of the typical differences reported in male and female landings disappeared. However, there were still some differences in muscular activation, and the women did exhibit greater quadriceps forces.

There is also some in vitro evidence that supports the contention that higher quadriceps forces might be a sex difference caused by structural factors. In particular, Wunschel and colleagues (30) simulated weight bearing squatting in male and female knees using cadavers. They found that in their higher loading condition, the female knees exhibited greater quadriceps forces, and that the difference increased with increasing TFJ flexion. What is important to note here is that because this was an in vitro study, there is no neuromuscular or coordination based explanation for this difference. Rather it is the structure of the specimens themselves that created the differences.

What are the therapeutic implications?

There is, therefore, credible evidence that might suggest that women express greater quadriceps forces during some movements, and that this might, in part, be due to differences in PFJ geometry. If this is the case, the most pertinent question for the therapist, is whether PFJ geometry can be altered, either by exercise or some other type of intervention. The primary candidate for such an intervention would be the P/Q ratio by altering either the patella flexion angle (ρ) or the quadriceps tendon angle (μ).

A common modelling assumption is that patella flexion angle (ρ) is a function of TFJ flexion (κ) alone. In reality, Seisler and Sheehan (14) demonstrated that only 60% of the variation in ρ is explained by κ , and suggested that this is a result of the extensibility of the patella tendon, meaning that the motion of PFJ and TFJ is partially decoupled. In particular, ρ is also sensitive to the distribution of loading experienced by the patella itself. For instance, Powers et al. (31) showed, in vitro, that if the quadriceps forces applied to the patella were multi-plane (as would be found in vivo), then patella flexion was less than when quadriceps forces were applied in a single plane (as would typically be the case in a model). More recently, in a magnetic resonance imaging study of patella kinematics, McWalter et al. (32) demonstrated that the relationship between ρ and κ was sensitive to the loading of the lower limb, and that ρ was reduced when the loading was greater. This finding is also supported by the radiographic study of Kim et al. (33), who found that ρ was reduced during weight-bearing, in comparison to an unloaded condition. It should be noted that all of these results are consistent with the suggestion that the patella tendon is extended by the greater loading, which in turn decreases the progression of the patella around the trochlea as the TFJ flexes, causing ρ to be reduced.

The other factor to consider is the direction of the quadriceps loading relative to the patella. As the quadriceps consists of at least four functionally different muscles (vastus lateralis, vastus intermedius, vastus medialis and rectus femoris), the resultant force acting on the patella is sensitive to the distribution of quadriceps loading. For instance, if there is a relatively greater contribution from rectus femoris, this will tend to shift the direction of the quadriceps line of action anteriorly, that is, it will decrease the quadriceps tendon angle (μ). As can be seen in Figure 4, this will increase the P/Q ratio meaning that less activation of the quadriceps is required to exert a given patella tendon force. Again, there is in vitro experimental evidence that has demonstrated that the P/Q ratio is increased if the line of

action of the quadriceps is directed more anteriorly (34), although this effect is likely to be the result of both the change in μ and a change in the patella flexion angle (ρ).

What these studies demonstrate is that there are various factors that affect the P/Q ratio, and that some of these might be modifiable with appropriate interventions. In fact, some commonly employed clinical interventions might create such effects, despite the fact that this is not the intended result. For instance, there has been a great deal of interest in the possibility of strengthening vastus medialis oblique (VMO) (35). This has been motivated by the fact that VMO exerts a medial force on the patella, and that this could potentially offset the lateral forces applied to the patella, thereby improving patella tracking in the frontal plane. However, as we have seen, one by product of such an intervention might be that the line of action of the quadriceps force (μ) is also changed. Alternatively, patella taping or knee braces are commonly used by patients who experience PFJ pain (36). Again, these interventions are often motivated by a desire to stabilise the patella in the frontal plane by providing some type of medial force to the patella. However, such interventions may also alter the relationship between the patella flexion angle (ρ) and TFJ flexion (κ) (37).

Conclusions

Although literature in this area is relatively scarce, it is credible to suggest that there may be sex differences in the geometry of the PFJ. Even if such differences are relatively modest, the functional anatomy of the PFJ means that they produce significant differences in quadriceps forces. This could, in turn, also explain differences in the epidemiology of knee injuries between men and women. Future work should seek to establish the existence and nature of sex differences in PFJ geometry as some aspects may be modifiable with exercise or therapeutic interventions.

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