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Influence of sex and knee joint rotation on patellofemoral joint stress

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Purpose: Females are two times as likely to experience patellofemoral pain syndrome (PFPS) than males, however, the reason for this difference between sexes remains unclear. Patellofemoral joint (PFJ) stress is believed to contribute to PFPS alterations through knee joint rotation alignment, but the influence of knee joint rotation conditions on PFJ stress is unclear. We aimed to investigate the influence of sex and knee joint rotation alignment on PFJ stress. *Methods*: Simulation ranges were set to knee joint flexion angles of 10–45° (common to both sexes) and extension moments of 0–240 Nm (males) and 0–220 Nm (females). The quadriceps force and effective lever arm length at the quadriceps muscle were determined as a function of the knee joint flexion angle and extension moment. The PFJ contact area, which is specific to sex, and knee joint rotation were calculated from cadaver data, and PFJ stress was estimated. *Results*: In all knee joint rotation conditions, PFJ stress was higher in females than in males. Additionally, PFJ stress in males and females was the largest under neutral conditions compared with other rotation conditions. *Conclusion*: The results of the present study may be useful for understanding the underlying mechanisms contributing to the differences in PFPS in males and females.

Key words: *patellofemoral joint stress, sex, knee joint rotation, contact area*

1. Introduction

Running is a readily accessible and popular mode of exercise that is necessary for maintaining a healthy lifestyle. Although running activity has many beneficial effects, running injuries are also likely to occur. A review article [24] has suggested that 19.3–79.3% of runners are injured each year. The majority of running injuries occur in the knee joint, and patellofemoral pain syndrome (PFPS) is a common orthopaedic trauma among runners [21]. Increased patellofemoral joint (PFJ) stress is a commonly accepted aetiological factor in the development of PFPS. PFJ stress [N/mm^2] indicates the PFJ reaction force per unit of PFJ contact area. PFJ reaction force results from the compression force acting on the knee joint, which depends on the knee joint angle and muscle force. Given that PFJ stress cannot be directly measured *in vivo*, many studies have estimated PFJ stress based on a mathematical model. There are two types of stress – normal stress and shear stress, and evidence has shown that normal stress is involved in the development of PFPS. For example, previous studies showed that individuals with PFPS exhibit greater PFJ stress compared to pain-free controls during fast walking [10], stair descent [25] and squatting [8]. Given the proposed relationship between PFJ stress and PFPS pathology, reducing PFJ stress during various activities is important to prevent the occurrence of PFPS or alleviate the symptoms of PFPS.

The incidence of PFPS is not equal between sexes. Female recreational runners are approximately two times more likely to experience PFPS than males [4], [21]. It is important to understand why the rate of

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occurrence of PFPS is more frequent in female runners as a first step towards prevention and treatment, however, the reason for the difference between sexes in the incidence of PFPS remains unclear. Some studies have investigated differences in PFJ stress during running in males and females, but there is no agreement between previous studies. Sinclair and Selfe [28] showed that PFJ stress was significantly higher in females than in males. This result provides insight into the high incidence of PFPS in females. However, another study [1] reported that PFJ stress in males was greater than that in females.

It is possible that the sex-specific PFJ contact area is not considered as one of the reasons why the results are inconsistent. As PFJ stress cannot be directly measured *in vivo*, PFJ stress has conventionally been calculated based on a mathematical model. The PFJ stress was calculated by dividing the PFJ reaction force by the PFJ contact area. The PFJ contact area can be calculated as a function of the knee joint angle, and some formulas have been described in a systematic review [15]. The PFJ contact area depends on the knee joint angle, but it has been shown that the PFJ contact area also differs depending on whether male and female [7]. For various knee flexion angles, the PFJ contact area was lower in females than in males [7]. Given that the PFJ contact area is different between sexes, PFJ stress needs to consider not only the knee joint angle but also sex. However, the authors of the above-mentioned studies [1], [28] did not calculate the PFJ stress considering the sex-specific PFJ contact area.

Additionally, the PFJ contact area is also influenced by the knee joint rotation. Patients with PFPS exhibit excessive knee rotation during running [14]. Previous studies have reported that knee joint internal rotation (IR) or external rotation (ER) alters the PFJ contact area [11], [17], and finally, changing the PFJ contact area alters the load applied to PFJ cartilage [2], [13]. Because female knees demonstrated significantly increased knee joint laxity and reduced stiffness compared with males [3], [18], females showed greater knee joint rotation than males during dynamic tasks [5], [20]. Thus, the PFJ contact area also needs to consider the factor of knee joint rotation for both males and females. A recent study [22] investigated the influence of knee joint angle and extension moment on PFJ stress, but did not consider the effects of sex and knee joint rotation. If we can determine which combination of sex and knee joint rotation have the highest PFJ stress, it may be useful to prevent and optimise treatment programs for PFPS.

Therefore, this study aimed to simultaneously investigate the influence of sex and knee joint rotation alignment on PFJ stress. We hypothesised that PFJ stress increase in females compared to in males in all knee joint rotation conditions.

2. Materials and methods

2.1. Model setting

The previously described PFJ model and calculation procedure (Fig. 1) were used to quantify the PFJ stress [6], [10]. We incorporated kinematic and kinetic data during running into this model since this study aimed to calculate PFJ stress during running. The PFJ stress referred in this study indicates normal stress. According to the flow chart presented in Fig. 1, the input variables required the knee joint flexion angle and extension moment. Prior to the calculation of PFJ stress, the simulation range of the knee joint extension moment and flexion angle were determined with reference to a previous study on running tasks [19] because PFPS is likely to occur during running activity.

Before the PFJ stress calculation, the simulation range of the knee joint extension moment and flexion angle were determined based on the result of previous studies. A previous study [19] reported differences between sexes in knee joint kinetics during running (recreational runners who trained at least 3 times per week and had a minimum of five years of distance running experience with a running speed of 4.0 m/s ± 5%; all runners had a rearfoot strike pattern). Considering the influence of sexes, we used the maximum values of the simulation range of knee joint moments from previous results. Specifically, a previous study [19] reported that the mean peak value of the knee joint

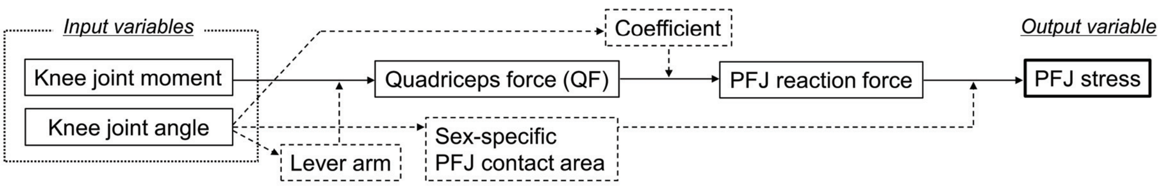

Fig. 1. Flow chart of patellofemoral joint (PFJ) kinetic calculation

extension moment during running in males and females was 3.04 Nm/kg and 3.47 Nm/kg, respectively. To calculate PFJ stress [N/mm^2], the moment was converted from Nm/kg to Nm by using the mean body mass of males (79.07 kg) and females (63.33 kg). Thus, the maximum values of the knee joint extension moment were 240.3 Nm (approximately 240 Nm) and 219.7 Nm (approximately 220 Nm) in males and females, respectively. While a slight knee joint flexion moment also occurs during running [19], the lower limit value was considered as 0 Nm because the knee joint flexion moment did not generate PFJ stress in the calculation. Thus, the simulation ranges of the moment were set from 0 to 240 Nm in males and 0 to 220 Nm in females. As shown in Fig. 1, for calculating the knee joint flexion angle, the quadriceps effective lever arm and PFJ contact area must be determined. Assuming the knee joint flexion angle in the stance phase during running, the simulation ranges of the knee joint angle were set from 10 to 45°, which is common to both sexes based on previous research [9].

The step sizes of the knee joint extension moment and flexion angle were 1 Nm and 1°, respectively. All combinations of knee joint flexion angle and extension moment (i.e., total – 16632 times, males – 8676 times = 36 (10–45°) angles × 241 (0–240 Nm) moments, females; 7956 times = 36 (10–45°) angles × 221 (0–220 Nm) moments) were calculated. In this study, informed consent was not required because it was a simulation study.

2.2. Sex-specific PFJ contact area calculation

To compute the PFJ stress specific to sex and specific knee joint rotation in the above-mentioned simulation ranges of the knee joint angle, this study calculated the PFJ contact area based on the cadaver data of Csintalan et al. [7]. The present study utilised the PFJ contact area of all knee joint flexion angles (0, 30, 60, and 90°) and rotation angle (IR, neutral [NT], ER) in males (average 70.8 years) and females (average 80.0 years) obtained from the previous study [7]. The cadaver data used in this study are listed in Table 1.

Table1. Patellofemoral joint contact area [mm^2] based on the cadaver data

Sex	Knee joint angle [°]	Internal rotation	Neutral	External Rotation
Male	0	172.6	174.3	176.9
	30	340.4	331.8	367.4
	60	354.9	346.3	384.3
	90	354.3	349.7	373.4
Female	0	149.5	152.4	177.3
	30	289.4	284.2	275.3
	60	260.9	216.5	256.5
	90	231.7	231.7	262.1

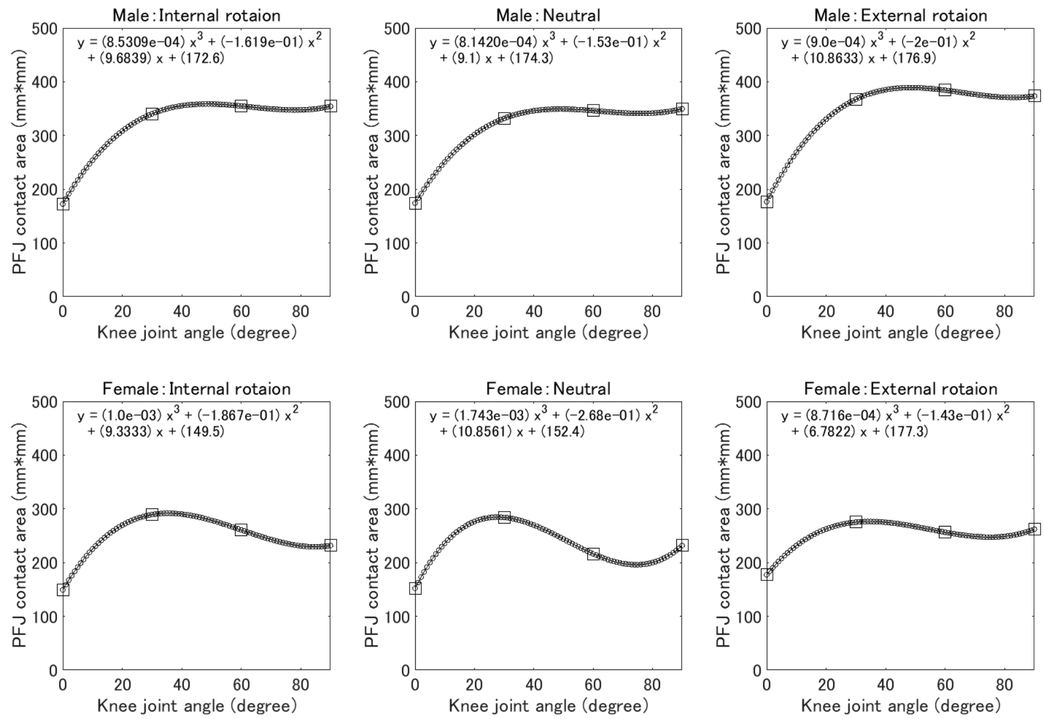

Fig. 2. The polynomial curves of patellofemoral joint (PFJ) contact area against knee joint angle. Squares each fitting curve show cadaver data. All polynomial curves passed all the measured contact areas obtained in cadaver data (Table 1)

According to the previous study [7], PFJ contact area was measured under conditions in which muscle forces were artificially generated in the cadavers by using a loading cable and pulley system. The muscle force was determined based on each cross-sectional muscle area (vastus medialis, 67 N; vastus intermedius/rectus femoris, 111 N; vastus lateralis, 98 N; iliotibial band, 27 N) [27]. A previous study investigated PFJ contact area under four conditions of knee joint angle (0, 30, 60, and 90°). However, PFJ stress cannot be calculated for other angle conditions because the PFJ contact area remains unknown. Other knee joint angles, such as 10 and 20°, are also observed during running. Thus, PFJ contact area can be calculated at various knee joint angles, equations of PFJ contact area calculation were calculated by third-order polynomial curve fitting to the contact areas in knee flexion angles (0, 30, 60, and 90°) for each knee joint rotation angle (IR, NT, ER) in males and females to provide contact areas in the simulation range of knee flexion. Polynomial curves of the PFJ contact area against the knee joint angle and polynomial equation for each knee joint rotation in males and females are shown in Fig. 2. All polynomial curves passed all the measured contact areas obtained in previous study (Table 1) [7] and had a fairly good fit. By using these polynomial equations, the PFJ contact area, which is specific to sex and knee joint rotation, was calculated in the simulation range of the knee joint angle (10–45°).

2.3. PFJ kinetic calculation

Based on previous studies [6], [10], the PFJ stress were calculated as follows: the quadriceps effective lever arm at each knee flexion angle of simulation range was determined using a fitting a non-linear equation [26] (Eq. (1)), where x is the knee flexion angle.

$$\text{Lever arm}\,(m) = 8\text{E}^{-8}x^3 + (-1.29\text{E}^{-5}x^2) + 2.8\text{E}^{-4}x + 0.0462. \quad (1)$$

The quadriceps force (F_q) was calculated by dividing the knee extension moment (M_{ext}) by the quadriceps effective lever arm (Eq. (2)).

$$F_q\,[\text{N}] = \frac{M_{\text{ext}}}{\text{Lever arm}}. \quad (2)$$

The PFJ reaction force was estimated by multiplying the quadriceps force by a coefficient [23] defining the relationship between the PFJ reaction force and knee joint flexion angle. Coefficient (k) is a constant defining the relation between quadriceps force and PFJ reaction force as a function of knee flexion angle (x). The coefficient was calculated for each knee joint flexion angle (Eq. (3)) and multiplied by quadriceps force to determine the PFJ reaction force (Eq. (4)).

$$k = \frac{-3.84\text{E}^{-5}x^2 + 1.47\text{E}^{-3}x + 0.462}{-6.98\text{E}^{-7}x^3 + 1.55\text{E}^{-4}x^2 - 0.0612x + 1}, \quad (3)$$

$$\text{PFJ reaction force}\,[\text{N}] = kF_q. \quad (4)$$

The PFJ contact area was calculated using a polynomial equation (Fig. 2) for each knee joint rotation in males and females. Finally, the PFJ stress was calculated by dividing the PFJ reaction force by the PFJ contact area (Eq. (5)).

$$\text{PFJ stress}\,[\text{N/mm}^2] = \frac{\text{PFJ reaction force}}{\text{PFJ contact area}}. \quad (5)$$

The above-mentioned steps were performed, and our study examined how differences in sex and knee joint alignments affect PFJ stress by changing the knee flexion angle and extension moment. All calculations were performed using a custom-written MATLAB code (R2019a; MathWorks Inc., Natick, MA, USA).

3. Results

In both sexes, PFJ stress increased as the knee joint extension moment increased, regardless of knee joint rotation (Fig. 3). Hence, when the knee joint extension moment decreased, PFJ stress also decreased. When the knee joint extension moment and flexion angle were at their maximum, PFJ stress showed the maximum value in all knee joint rotations in both sexes. Additionally, when the knee joint extension moment was at its maximum, the knee joint flexion angle at which the PFJ stress reached its minimum value when was slightly different in knee joint rotation for males and females.

The maximum values of PFJ stress (i.e., maximum knee joint extension moment and flexion angle) in the knee joint rotation condition in males and females are shown in Fig. 4. In all knee joint rotation conditions, PFJ stress was higher in females than in males. PFJ stress of males was largest in the NT condition and smallest in the ER condition. PFJ stress in females was largest in the NT condition, as in males, but was smallest in the IR condition.

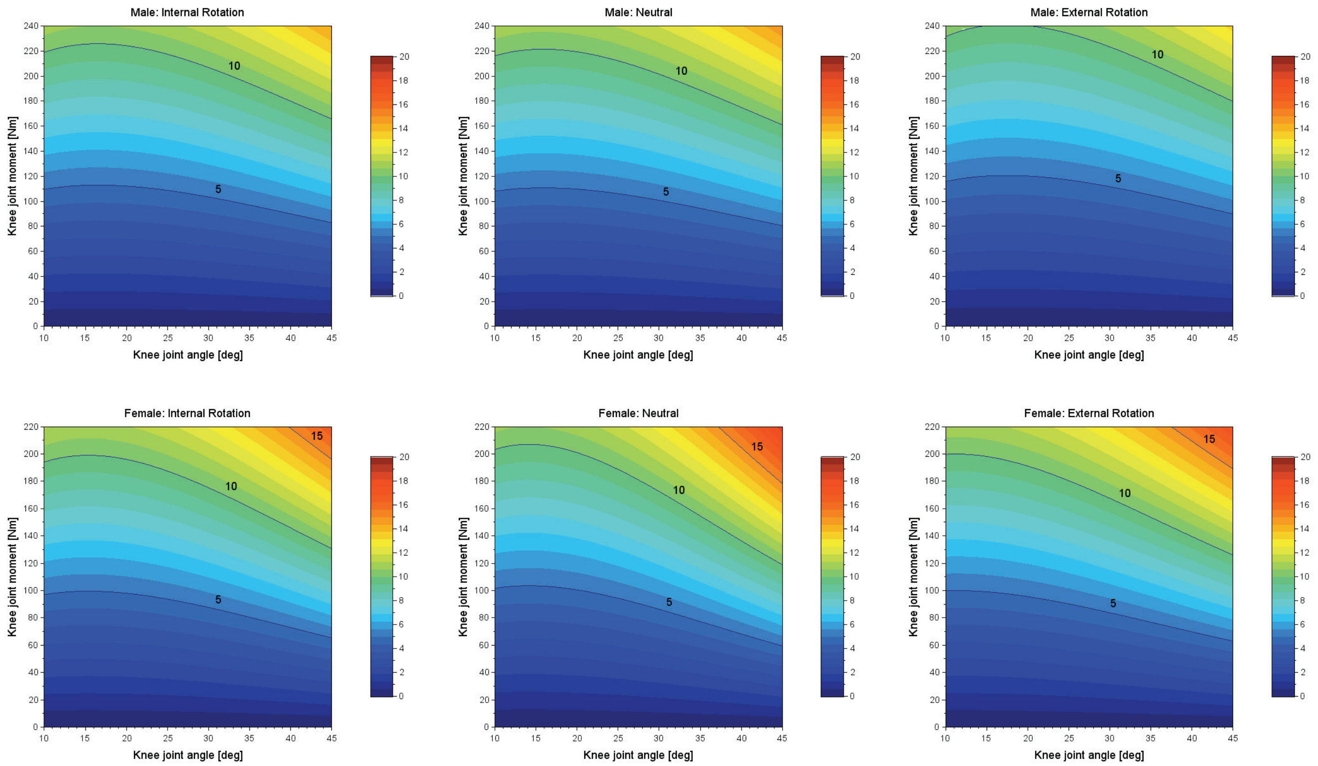

Fig. 3. Contour lines of patellofemoral joint stress on a two-dimensional plot of knee joint extension moment and flexion angle

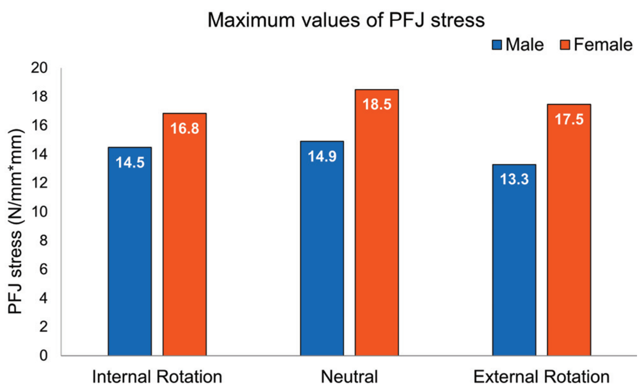

Fig. 4. Maximum values of patellofemoral joint (PFJ) stress in knee joint rotation conditions in both sexes

4. Discussion

This study aimed to investigate the influence of sex and knee joint rotation on PFJ stress. To elucidate the reason for this difference between sexes in the incidence of PFPS, previous studies [1], [28] have investigated sex differences in PFJ stress during running. Additionally, patients with PFPS exhibit excessive knee rotation during running [14]. However, they [1], [28] did not consider sex-specific and knee rotation-specific PFJ contact area regardless of PFJ contact area differs between males and females, among knee joint rotation conditions [7]. To the best of our knowledge, the present study is the first to simultaneously investigate the influence of sex and knee joint rotation alignment on PFJ stress.

In this study, PFJ stress was maximum when the knee joint extension moment and flexion angle were at the maximum, regardless of sex and knee rotation conditions (Fig. 3). These findings are consistent with those of previous studies [12], [30]. An increase in knee joint extension moment is associated with an increase in the quadriceps force and PFJ reaction force, which ultimately leads to an increase in PFJ stress. Moreover, an increase in knee joint flexion angle leads to an increase in the demand for the quadriceps muscles. Lenhart et al. [12] showed that the PFJ reaction force is low when the knee joint angle is low during running, thus, the peak knee flexion angle is a good predictor of the PFJ reaction force ($R^2 = 0.68$). In contrast, the knee joint angle was not the minimum value (i.e., 10°) when PFJ stress was the minimum value. A previous study [22] discussed that PFJ stress is not necessarily low when the knee joint flexion angle is at its maximum value, which supports the results of the present study.

In all knee joint rotation conditions, females showed increased maximum PFJ stress compared to males (Fig. 4), and these results were consistent with our hypothesis. The observed differences between males and females in the present study are likely due to the PFJ contact area. Based on a previous study data set [19], the maximum simulation range in the knee joint extension moment was set at 240 Nm and 220 Nm in males and females, respectively. The PFJ reaction is calculated based on the knee joint extension moment, and it is associated with the joint moment magnitude. Thus, the PFJ reaction force in females was lower than that in males at all knee flexion angles (Fig. 5). However, PFJ stress is influenced not only by the PFJ reaction force but also by the PFJ contact area, and the PFJ contact area in females was lower than that in males [7] (Fig. 5). Therefore, even if the PFJ reaction force was small in females, the PFJ contact area was also small in females, and ultimately, PFJ stress was considered to be high in females. Female recreational runners had a higher incidence of PFPS than males [4], [21], but no agreement of PFJ stress during running for males and females has been reported in previous studies [1], [28]. Since previous studies did not consider the sex-specific PFJ contact area, the discrepancy in the results between previous studies may be explained by the results of the present study. Additionally, the results of the present study may be useful in understanding the reason behind the sex difference in the incidence of PFPS.

Additionally, PFJ stress maximum values differed among knee joint rotation conditions for males and females, which is also considered to be due to the PFJ contact area as well as the reason for sex differences in PFJ stress. The results presented in Fig. 5 indicates that the PFJ contact area is different among knee joint rotation conditions, and previous studies [7], [11], [17] have also reported that the PFJ contact area is influenced by knee joint rotation. PFJ stress is the highest in the NT condition for both males and females, which is thought to be due to the small PFJ contact area at the knee joint maximum angle (45°). Previous studies have shown that knee rotation during running differs between patients with and without PFPS [14] and between sexes [5], [29]. The present results of PFJ stress considering knee rotation will be useful for understanding the treatment of PFPS and the mechanism of PFPS development.

Our findings may be beneficial for reducing symptoms in patients with PFPS and/or preventing the occurrence of this condition in runners. Elevated PFJ stress is considered the cause of PFP in runners. Powers et al. [16] reported that wearing a knee brace when fast walking reduces pain (56% reduction by a 10-point visual analogue scale) in patients with PFP because of the decreased PFJ stress. Furthermore, a previous study [16] showed that pain decreased when wearing a knee brace due to a 1 MPa change in PFJ stress. In the present study, for example, sex difference of PFJ stress was at least 2.3 MPa (IR condition), and differ-

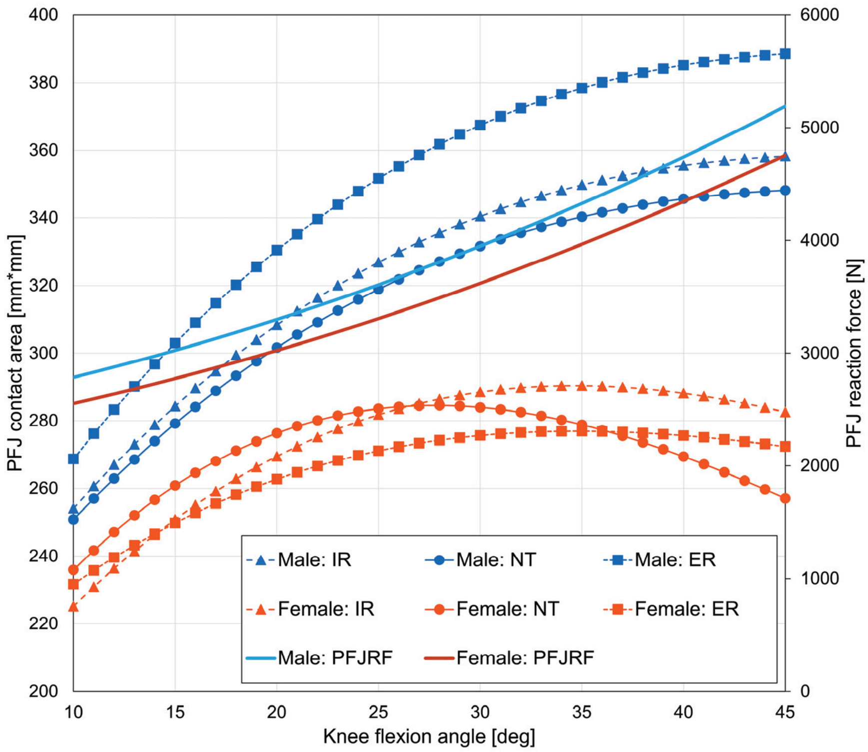

Fig. 5. Patellofemoral joint (PFJ) contact area and PFJ reaction force against knee flexion angle.
IR – internal rotation; NT – Neutral; ER – External rotation; PFJRF – PFJ reaction force

ence of PFJ stress between NT and ER conditions were 1.6 MPa and 1.0 MPa in males and females, respectively (Fig. 4). Hence, the difference in PFJ stress between sexes and among knee joint rotation in this study may be meaningful for reducing pain.

The present study has some limitations. First, we calculated the specific (sex and knee rotation) PFJ contact area, but the contact area was based on cadaver data from a previous study [7]. Therefore, it is different from the contact area *in vivo*. Consequently, PFJ stress may also be different from the present results. However, since PFJ stress cannot be directly measured *in vivo*, the most of previous studies use the contact area of cadaver data as in the present study. Second, the PFJ contact area data were extracted from a cadaveric study in elderly individuals [7]. PFJ contact areas may differ between the young and elderly populations. Thus, it may be difficult to generalise our findings to the young running population. Finally, other anatomical factors, such as the muscles and bone structure of each participant, were not considered. Since these structures differ between sexes, incorporating these anatomical factors into the calculations might have altered our results. Therefore, these limitations should be addressed in future studies.

In conclusion, our study found that two factors (sex and knee rotation) affect PFJ stress. The results may be useful for understanding the underlying mechanisms contributing to the differences in PFPS in males and females. Additionally, this study suggests that it is important to consider the effect of knee joint rotation when considering PFJ stress.

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Conflict of Interest

The authors report no conflicts of interest.

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