

A mathematical modelling study investigating the influence of knee joint flexion angle and extension moment on patellofemoral joint reaction force and stress

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ARTICLE INFO

Article history:

Received 17 February 2019

Received in revised form 4 October 2019

Accepted 17 October 2019

Keywords:

Knee joint angle

Knee joint moment

Patellofemoral joint kinetics

ABSTRACT

Background: Patellofemoral pain (PFP) is the most common orthopaedic condition among runners. Individuals with PFP exhibit greater patellofemoral joint (PFJ) reaction force and stress when compared with pain-free controls. However, it is not clear whether PFJ reaction force and stress are the highest (or lowest) when knee joint flexion angle and extension moment are in which combinations. We aimed to investigate the influence of knee joint flexion angle and extension moment on PFJ reaction force and stress.

Methods: A PFJ sagittal model was used to quantify PFJ reaction force and stress. Based on the public dataset of the previous study, peak knee joint flexion angle and extension moment at various running speeds was calculated. Based on the calculated peak value, simulation ranges were set to knee joint flexion angle of 10–45° and extension moment of 0–240 Nm. The quadriceps force, effective lever arm length at quadriceps muscle, and PFJ contact area were determined as a function of the knee joint flexion angle and extension moment, and finally PFJ forces and stress were estimated.

Results: PFJ reaction force increased as the knee flexion angle and extension moment increased. Although PFJ stress also increased as the knee extension moment increased, it was at the highest and lowest at 10° and about 30° knee joint flexion angles, respectively.

Conclusions: Incorporating knee flexion posture (approximately 30°) during running may help in reducing PFJ stress, which would be useful in the prevention of pain and act as an optimal treatment program for PFP.

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1. Introduction

The increased awareness of exercise as a necessity for maintaining a healthy lifestyle has made running more popular than ever. In the United States, the number of people registering for road races in 2018 was 18.1 million [1]. Although running activity has many beneficial effects, running injuries are also likely to occur. A review article [2] suggested that 19.4–79.3% of runners are injured each year. Patellofemoral pain (PFP) is the most common orthopaedic condition among runners [3]. In a previous study, it

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was reported that individuals with PFP exhibit greater patellofemoral joint (PFJ) reaction force and stress when compared with pain-free controls during fast walking [4]. Therefore, the occurrence of PFP among runners is believed to be contributed to by the elevated PFJ kinetics. The repetitive application of elevated PFJ forces and stress to the patellar articular cartilage at a high loading rate may contribute to PFP by increasing patellar interosseous pressure [5].

PFJ kinetics are associated with knee joint flexion angle and extension moment. Given that PFJ reaction force and stress cannot be directly measured *in vivo*, a previous study [6] estimated PFJ reaction force and stress based on a mathematical model. This model can determine quadriceps force, effective lever arm length at quadriceps muscle, and PFJ contact area as a function of the knee joint angle and moment. Finally, PFJ reaction forces and stress are estimated. Previous studies [6–10] investigated several strategies to reduce PFJ reaction force and stress by using this model. For example, a recent study [8] reported that running in combination with a minimalist shoe and increased cadence reduced knee joint extension moment. Furthermore, this condition reduced approximately 30% of PFJ peak reaction force and stress compared with the control condition. Moreover, Roper et al. [11] reported that the forefoot strike pattern led to increase knee flexion angle. Consequently, this strategy resulted in reduction of PFJ stress and knee pain in patients with PFP.

PFJ reaction force and stress measurements have been reported during different activities, such as running [8], walking [4], and also in different populations, such as in patients with PFP [12], and patella alta [13]. However, despite that the fact knee joint flexion angle and extension moment are involved in PFJ kinetics, it is not clear whether PFJ reaction force and stress are the highest (or lowest) when knee joint flexion angle and extension moment are in which combinations. It would be useful to be able to understand the combination of knee joint flexion angle and extension moment when PFJ kinetics are the highest or lowest, because prevention of and optimal treatment programs for PFP are essential to keep runners active. Thus, this study aimed to investigate the influence of knee joint flexion angle and extension moment on PFJ kinetics through mathematical modelling. We hypothesised that there would be an increase in the PFJ reaction force and stress as the knee joint flexion angle and extension moment increased.

2. Methods

2.1. Model setting

A previously described PFJ sagittal model was used to quantify PFJ reaction force and PFJ stress [4,6]. Given that PFJ reaction force is normalised by body mass, the body mass of the model was set to 70 kg with reference to the body mass of the subjects targeted by previous studies [4,14]. Because this study was a mathematical modelling study, obtaining informed consent was not required. Prior to the calculation of PFJ reaction force and stress, simulation range of knee joint flexion angle and extension moment were decided with reference to a previous study [14]. Using the public dataset of Fukuchi et al. (<http://demotu.org/datasets/running/>), the peak values of knee joint flexion angle and extension moment during stance phase of 2.5 m/s, 3.5 m/s, and 4.5 m/s were calculated so that the results of this study could be applied to various running speeds. The peak value of the knee joint flexion angle was 44° to 12° , and the knee joint extension moment was 235 Nm to -51 Nm during the stance phase (total average of 28 subjects). Therefore, the simulation ranges were set as follows: knee joint angle, 10 – 45° and knee extension moment, 0 – 240 Nm. Given that the negative value (-51 Nm) of knee joint moment indicates knee joint flexion moment, the lower limit value was 0 Nm. Step size of knee joint flexion angle and extension moment was one degree and one Newton metre, respectively, and all combinations of knee joint flexion angle and extension moment (i.e. 8676 times = 36 (10 – 45°) angles \times 241 (0 – 240 Nm) moments) were calculated.

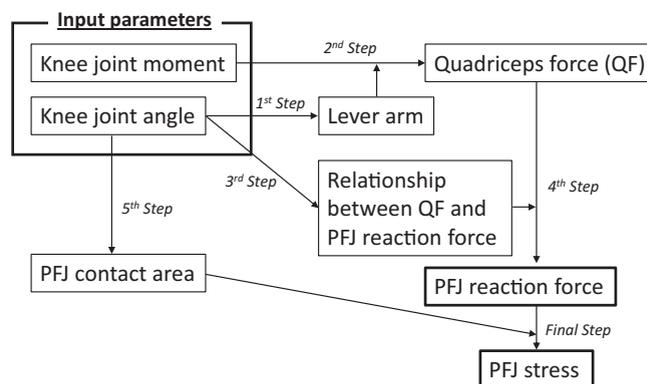


Figure 1. Flow chart of patellofemoral joint (PFJ) kinetic calculation.

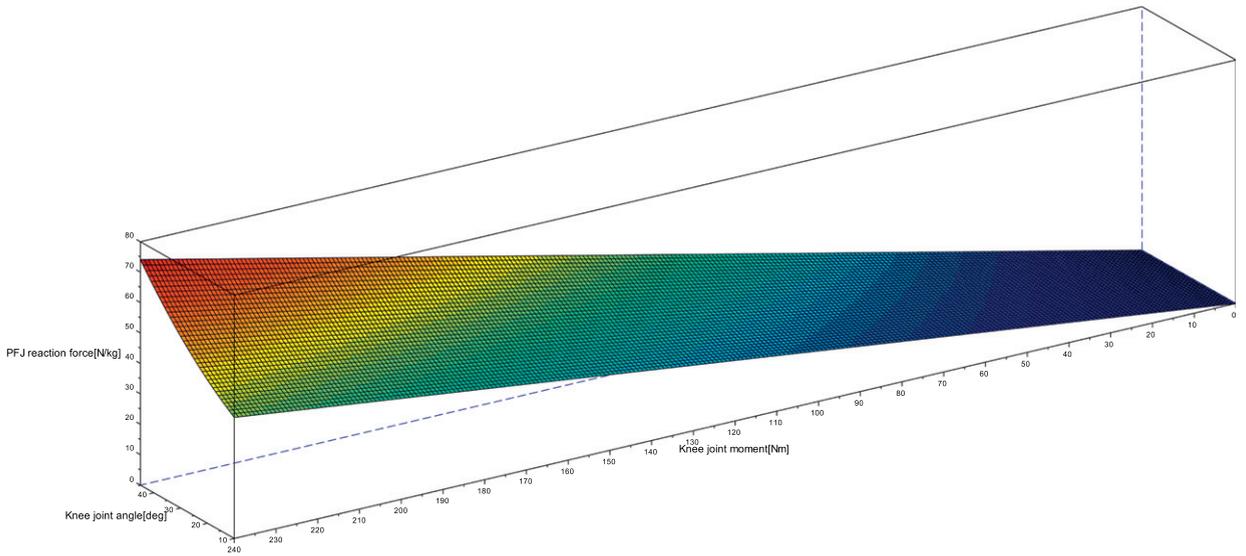


Figure 2. Relationship between knee joint extension moment, flexion angle, and patellofemoral joint (PFJ) reaction force.

2.2. PFJ kinetic calculation

The flow chart of PFJ kinetic calculation is shown in Figure 1. The input variables required were knee joint flexion angle and extension moment. PFJ reaction force and PFJ stress were calculated as follows: the quadriceps force was calculated by dividing the net knee extension moment by the quadriceps effective lever arm. The quadriceps effective lever arm was determined at each knee flexion angle by fitting a non-linear equation to the data [15]. PFJ reaction force was estimated by multiplying the quadriceps force by a constant [16] that defines the relationship between PFJ reaction force and knee flexion angle. PFJ reaction force was normalised by body mass. PFJ contact area was estimated by fitting ($R^2 = 0.98$) a fourth-order polynomial curve algorithm to the seven contact areas (83, 140, 227, 236, 325, 211, and 199 mm²) for seven knee flexion angles (0°, 15°, 30°, 45°, 60°, 75°, and 90°) as reported by Powers et al. [17] to provide continuous contact areas from 0° to 90° of knee flexion. Finally, the PFJ stress was calculated by dividing the PFJ reaction force by the PFJ contact area.

In the present study, the above-mentioned steps were performed, and the effect of changes in knee joint flexion angle and extension moment on the PFJ reaction force and stress was evaluated. All calculations were performed using custom-written SCILAB code version 6.0.0 (Enterprises, Versailles, France).

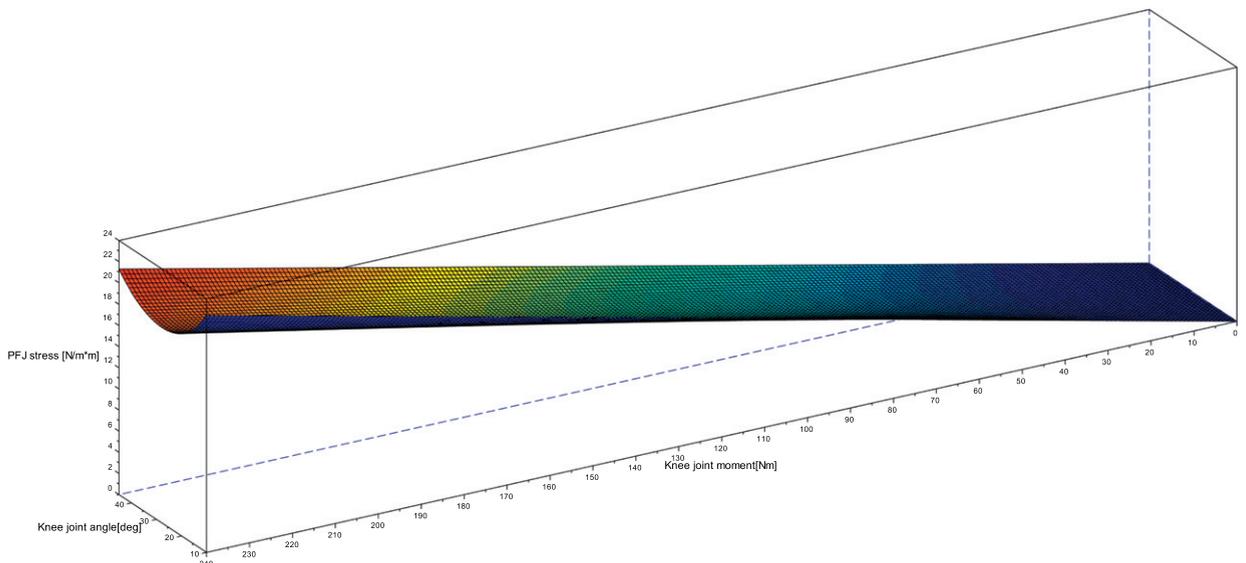


Figure 3. Relationship between knee joint extension moment, flexion angle, and patellofemoral joint (PFJ) stress.

3. Results

PFJ reaction force increased as the knee flexion angle and extension moment increased (Figure 2). Hence, when the knee joint flexion angle and extension moment decreased, PFJ reaction force also decreased. When the knee joint extension moment was at its maximum value (240 Nm), PFJ reaction force showed the maximum value (74.1 N/kg) at the maximum knee joint flexion angle (45°), and the minimum value (39.7 N/kg) at the minimum knee joint flexion angle (10°).

PFJ stress also increased as the knee extension moment increased as well as the relationship between PFJ reaction force and knee extension moment. However, the relationship between PFJ stress and knee joint flexion angle differed from the relationship between PFJ stress and knee joint extension moment (Figure 3), wherein PFJ stress decreased at 28° knee joint flexion angle. When the knee joint extension moment was at the maximum (240 Nm), PFJ stress showed the maximum value (22.4 N/mm²) at 10° knee joint flexion angle, and the minimum value (18.5 N/mm²) at 28° knee joint angle (Figure 4). Additionally, PFJ stress was consistently at its lowest at a knee joint flexion angle of 28° among all knee joint extension moment values (Figure 5).

4. Discussion

Several studies [6–10,18] have investigated the strategy to reduce the magnitude of PFJ kinetics in different tasks. A common observation among these studies is that PFJ kinetics during running become lower by taking off the shoes, changing from rearfoot to forefoot strike patterns, or performing higher step rates, thereby resulting in knee joint angle and moment change during running, and consequently decreased PFJ kinetics. Based on these findings, knee joint flexion angle and extension moment are associated with PFJ kinetics, but it is not clear whether PFJ reaction force and stress are at their highest (or lowest) when knee joint flexion angle and extension moment are in which combinations. As we hypothesised, our results found that PFJ reaction force increased as the knee joint flexion angle and extension moment increased. However, while PFJ stress also increased as the knee joint extension moment increased, PFJ stress and knee joint flexion angle exhibited a different relationship. When the knee joint extension moment is at the maximum, PFJ stress showed the maximum value at 10° knee joint flexion angle, and the minimum value at 28° knee joint flexion angle; these findings differed from our hypothesis.

The finding that PFJ reaction force increased as the knee joint flexion angle and extension moment increased was consistent with that of previous studies [6,8,18,19]. The reduction in the PFJ reaction force occurred due to the smaller knee flexion angle during the stance phase of running, which decreases the demand on the quadriceps muscles [6]. Lenhart et al. [18] have also reported that PFJ reaction force is low when the knee joint angle during running is low; thus, peak knee flexion angle is a good predictor of patellofemoral force according to the results of the univariate regression analysis ($R^2 = 0.68$). Therefore, it is thought that PFJ reaction force increased as the knee joint flexion angle and extension moment increased.

PFJ stress also increased as the knee extension moment and PFJ reaction force increased, which is due to the increased PFJ reaction force caused by the increased knee joint moment. However, PFJ stress was highest at 10° knee joint flexion angle, and lowest at about 30° knee joint flexion angle. These results are different from those observed between PFJ stress and knee joint extension moment. Because PFJ stress is obtained by dividing the PFJ force by the contact, PFJ stress is influenced by both PFJ force and contact area. That is, PFJ stress would be at its lowest when PFJ reaction force is low and PFJ contact area is large. For example, while the contact area continues to go up as the knee flexion angle increases, the PFJ reaction force also continues to go up as knee flexion angle increases (Figure 6). When the knee joint flexion angle is at its maximum value (45°), the contact

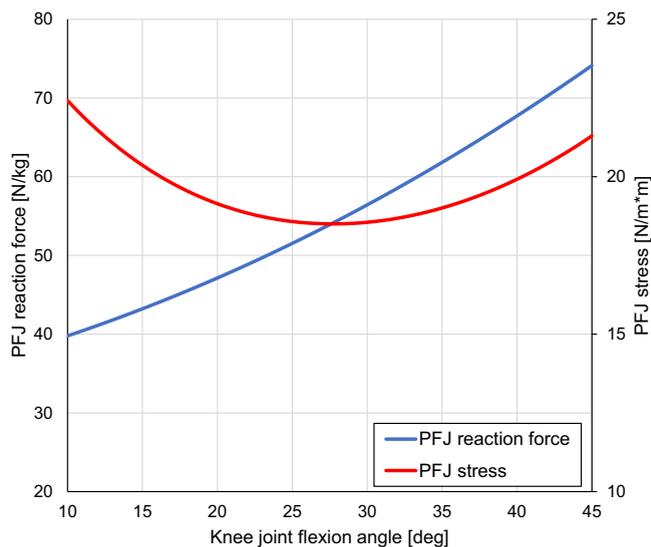


Figure 4. Patellofemoral joint (PFJ) reaction force and PFJ stress against knee flexion angle at a constant 240 Nm.

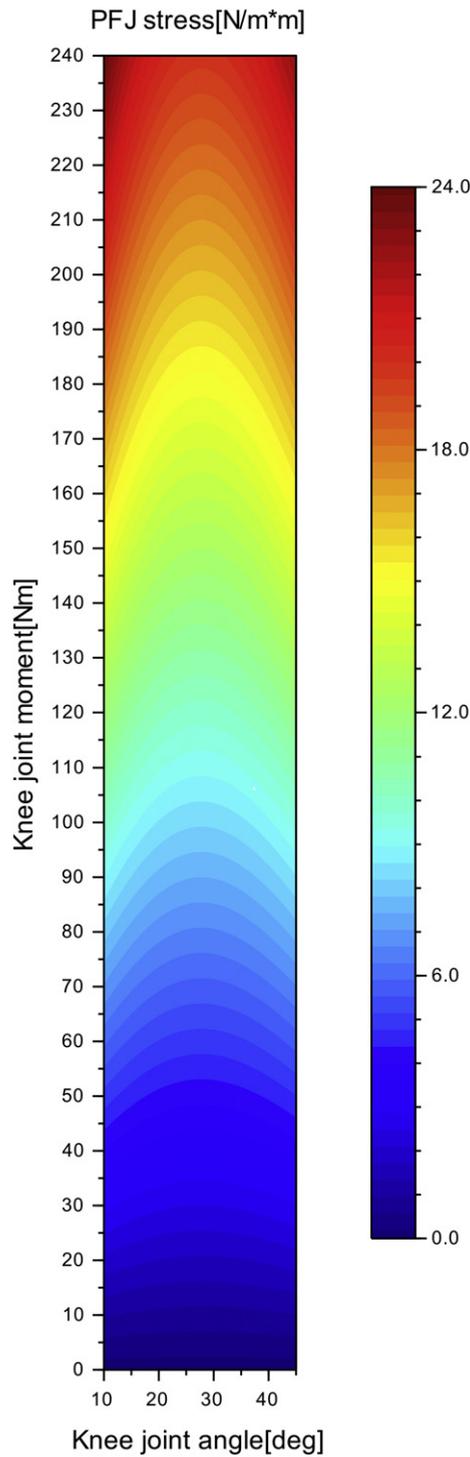


Figure 5. Contour lines of patellofemoral joint (PFJ) stress on a two-dimensional plot of knee joint extension moment and flexion angle.

area and PFJ reaction force are at their maximum value of 243 mm² and 5188.3 N, respectively. Therefore, PFJ stress is not necessarily at its lowest when the knee joint flexion angle is at its maximum value. In contrast, when the knee joint flexion angle is at its minimum value (10°), the PFJ reaction force and contact area are at their minimum value of 2784.5 N and 124.1 mm², respectively. Therefore, although the PFJ reaction force is at the lowest when the knee joint flexion angle is at its minimum value, the contact area is also at its lowest; thus, PFJ stress does not decrease. Considering the above-mentioned data, PFJ

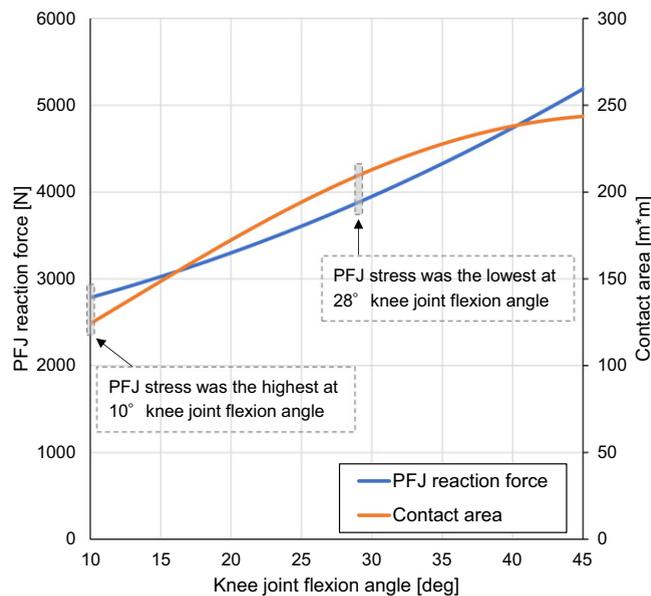


Figure 6. Patellofemoral joint (PFJ) stress and contact area against knee flexion angle at a constant of 240 Nm.

stress is determined by the relationship of both PFJ reaction force and contact area, and it is considered that PFJ stress was at its lowest or highest at a specific knee joint flexion angle, such as 28° or 10°, respectively.

Our findings may be beneficial for reducing symptoms in patients with PFP and/or for preventing the occurrence of this condition in runners. Elevated PFJ kinetics is thought to be the aetiology of PFP among runners, and patients with PFP exhibit elevated PFJ reaction force and PFJ stress [4,20]. Powers et al. [21] reported that wearing a knee brace when walking immediately reduces pain in patients with PFP because of the decreased PFJ stress. Furthermore, a previous study [21] reported that pain is decreased when wearing a knee brace due to a one-megapascal change in PFJ stress. In the present study, among the knee joint extension moment values, PFJ stress was consistently at its lowest and highest at 28° and 10° knee joint flexion angle, respectively (Figure 5). Thus, the angle of approximately 30° is always optimal for minimising PFJ stress. In the present results, PFJ stress had a 3.9-MPa change when the knee extension moment was at its maximum value (240 Nm) at knee joint flexion angles of 10° and 28°. Furthermore, in cases wherein the knee joint extension moment was one-third (i.e. 80 Nm) of the maximum value, PFJ stress had a 1.3-MPa change at knee joint flexion angles of 10° and 28°. Hence, even if the knee joint extension moment was one-third of the maximum value, knee pain may be decreased, according to the results of a previous study [21]. If a patient with PFP exhibits reduced knee flexion during running, it may be helpful to encourage them to increase (i.e. approximately 30°) knee flexion when running because PFJ stress may be decreased.

The present study has certain limitations. Firstly, the model utilised to estimate PFJ stress was a simplified planar model; thus, this does not take into consideration the individual three-dimensional patella. It is possible that the individual alterations in the patella kinematics may affect the contact area, thereby affecting the PFJ stress. Secondly, the model in this study did not include joints other than PFJ. Previous studies have reported hip adduction and internal rotation, and knee external rotation during running differed between PFP patients and pain-free controls [22,23]. Another study [24] has reported that change in sagittal plane trunk posture influences PFJ kinetics during running. However, this study did not investigate these factors. In addition, this study demonstrated that adjusting the knee joint flexion angle to approximately 30° during running may be helpful in reducing pain. However, even if the knee joint angle of 30°, which reduces the PFJ stress and pain, can be achieved, the stress on other joints may be greater. Finally, this study cannot calculate the specific PFJ contact area. A previous study demonstrated that contact area in patients with PFP was less when compared with the control group [4]. Thus, the findings of this study cannot be generalised to the PFP group. These limitations will need to be addressed in future studies.

5. Conclusion

PFJ reaction force increased when the knee joint flexion angle and extension moment increased. However, while PFJ stress also increased as the knee joint extension moment increased, it was at its highest at 10° knee joint flexion angle and at its lowest at approximately 30° knee joint flexion angle. Incorporating a slight knee flexion posture (approximately 30°) during running may help in reducing PFJ stress, which would be useful in the prevention of pain and would act as an optimal treatment program for PFP.

Ethics committee letter

Given that this study was a computer simulation, obtaining informed consent was not required.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Acknowledgements

We thank the members of our institution for their assistance and Editage (www.editage.jp) for the British English language editing.

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