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Increasing Step Frequency Reduces Patellofemoral Joint Stress and Patellar Tendon Force Impulse more at Low Running Speed

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ABSTRACT

Purpose: Patellofemoral pain syndrome and patellar tendinopathy are important running-related overuse injuries. This study investigated the interaction of running speed and step frequency alterations on peak and cumulative patellofemoral joint stress (PFJS) and patellar tendon force (PTF) parameters. **Methods:** Twelve healthy individuals completed an incremental running speed protocol on a treadmill at habitual, increased and decreased step frequency. Peak PFJS and PTF, peak rate of PFJS and PTF development and PFJS and PTF impulse per kilometre (km) were calculated using musculoskeletal modelling. **Results:** With increasing running speed, peak PFJS ($p<0.001$) and PTF ($p<0.001$) and peak rate of PFJS ($p<0.001$) and PTF ($p<0.001$) development increased, while PFJS ($p<0.001$) and PTF ($p<0.001$) impulse per km decreased. While increasing step frequency by 10%, the peak PFJS ($p<0.001$) and PTF ($p<0.001$) and the PFJS ($p<0.001$) and PTF ($p<0.001$) impulse per km decreased. No significant effect of step frequency alteration was found for the peak rate of PFJS ($p=0.008$) and PTF ($p=0.213$) development. A significant interaction effect was found for PFJS ($p<0.001$) and PTF ($p<0.001$) impulse per km suggesting that step frequency alteration was more effective at low running speed. **Conclusions:** The effectiveness of step frequency alteration on PFJS and PTF impulse per km is dependent on the running speed. With regard to peak PFJS and PTF, step frequency alteration is equally effective at low and high running speeds. Step frequency alteration was not effective for peak rate of PFJS and PTF development. These findings can assist the optimisation of patellofemoral joint and patellar tendon load management strategies.

Key Words: PATELLOFEMORAL PAIN SYNDROME, PATELLAR TENDINOPATHY, LOAD MANAGEMENT, RUNNING MECHANICS

INTRODUCTION

Running has grown in popularity in the past six decades due to its accessibility, major health benefits and low cost (1, 2). On the other hand, running poses a major injury risk, with injury prevalence numbers of 44.6% on average (3). More than 70% of these running-related injuries is associated with overuse (3). The knee joint is cited as the most common region for running-related injuries, with patellofemoral pain syndrome and patellar tendinopathy among the most prevalent ones (3–5). These overuse injuries occur when cumulative tissue microdamage exceeds the adaptive capacity of that tissue (6, 7). Load management is therefore an important aspect in the prevention and rehabilitation of both patellofemoral pain syndrome (8) and patellar tendinopathy (9).

Tissue microdamage during running is the result of a combination of the peak load per step and the cumulative load per kilometre (km) (10). Biomechanical load parameters that are typically investigated for their association with overuse injuries are peak load and peak rate of load development per step and load impulse per km (10, 11). An intervention that is often used to reduce these load parameters during running, is the alteration of the step frequency. Several studies have provided supportive evidence that an increased step frequency can reduce peak and impulse measures of patellofemoral joint stress (PFJS) and peak measures of patellar tendon force (PTF) for an individual step (12, 13). During these studies, the running speed was kept constant over the different step frequency conditions. The effect of running speed itself has also gained increasing interest over the last years. Several studies suggest that an increase in running speed is accompanied by a decrease in impulse per km, because of the decreased number of steps per km and contact time per step (14, 15). Remarkably, the interaction effect of running speed and step frequency alteration on PFJS and PTF has not yet been investigated. In other words, whether the effect of step frequency alterations is different at high compared to low running speeds, remains unknown. Therefore, the objective of this study was to investigate whether the load-modifying effect of step frequency alterations was similar at different running speeds. More specifically, the load parameters of interest were the peak PFJS and PTF per step, the peak rate of PFJS and PTF development per step, and the PFJS and PTF impulse per km running. We hypothesised that an interaction effect between running speed and step frequency alterations will be present for these three load parameters since the combination of high running speed and increased step frequency might trigger a shift in the running style, including the ratio between contact time and flight time, vertical excursion of the centre of mass, range of motion in the different joints and foot strike pattern (16–18).

METHODS

Participants

Thirteen participants were recruited among students of the Faculty of Movement and Rehabilitation Sciences, KU Leuven (BEL). The participants were recreationally active runners without a lower limb injury or low back pain in the past six months and without a history of major lower limb injury that required surgery. No specific criterion was set in terms of minimum weekly running distance. An a-priori sample size calculation was performed in G*Power 3.1 (19). For an arbitrary moderate effect size Cohen's f of 0.3 and an alpha of 0.008, 12 participants were necessary to detect significant interaction effects with a statistical power of 0.80 or higher. An alpha of 0.008 was used as a Bonferroni correction was applied (dividing an alpha value of 0.05 by the number of load parameters, i.e. six). The study was approved by the ethical committee of research UZ/KU Leuven (reference number: S62706). All participants provided written informed consent before the start of the data collection.

Protocol

The running protocol was performed on an instrumented treadmill (Motek Medical, Amsterdam, NL). All participants wore the same type of shoe (Indoor Copa, Kelme, Elche, ESP). A five-minute warm-up run at a self-selected speed was performed before the beginning of the data collection. Next, the participants completed three repetitions of an incremental speed protocol. This protocol started at an initial running speed of 8km/h and increased by 2km/h every minute until the speed of 16km/h was reached. During the first repetition, participants ran at their preferred step frequency. The step frequency per minute was determined at each running speed by counting the number of contacts from one foot during a 30-second interval and multiplying this number by four (17, 20, 21). During the second and third repetition of the protocol, the participants were instructed to either increase or decrease their step frequency by 10% according to audible cues of a metronome. The order of the altered step frequency conditions was randomised for each participant using a coin toss. An eight-minute resting period in between repetitions of the protocol was provided to avoid fatigue effects. This could, however, be extended if the participant self-indicated that more rest was needed. In order to verify whether systematic fatigue effects were present, the rate of perceived muscle exertion was monitored at the end of each running speed block using a CR100 scale (22). The participant had to provide a fatigue score between 0: “nothing at all”, and 120: “absolute maximum”. The results can be found in Supplemental Table 1 (see Supplemental Digital Content, Mean ± SD values for rate of perceived leg muscle exertion, http://links.lww.com/MSS/C853).

Data collection

Kinematics of the lower limbs and trunk were collected at a sampling frequency of 100Hz by 13 cameras of a passive marker-based motion capture system (Vicon, Oxford, UK). Reflective markers were placed according to the Liverpool John Moores University model (23). Ground reaction forces (GRF) were measured at a sampling frequency of 1000Hz using two force plates embedded in the instrumented treadmill (24). Marker and GRF data were collected over a 15-second time interval during the steady state phase of each running speed block. That steady state phase was defined by two characteristics. First, the trunk of the participant did not make any horizontal motion relative to the treadmill, indicating that the participant was running at the desired running speed. Second, the participant had to match the step frequency indicated by the metronome. Both aspects were visually verified by two of the researchers who were present during the protocol (20, 25). Data collection only started when both researchers confirmed these criteria have been met.

Data processing

The stance phases of 10 valid steps for one leg were retained for further analysis. The choice of which leg would be analysed, was randomised by a coin toss. Marker and GRF data were low-pass filtered with a cut-off frequency of 18Hz. A 20N threshold of the vertical component of the GRF marked the start and end of the stance phase.

Musculoskeletal modelling was performed in OpenSim 3.3 (OpenSim, Stanford, CA, USA) (26). The Catelli model was used as generic musculoskeletal model for this study because it has its muscle properties based on young and active individuals and it includes a patellofemoral joint and patellar tendon (27). It also includes refined knee joint improvements capable of simulating fast running (28), while controlling the muscle paths during large ranges of the knee and hip joints (29). This full-body model consists of 37 degrees of freedom (DoF). The lower limbs of this model consisted of a 6 DoF pelvis, a 3 DoF ball-and-socket hip joint, a 1 DoF tibiofemoral joint, a 1DoF patellofemoral joint, and a 1 DoF ankle joint. The motions of the lower limb were driven by 80 Hill-type muscle-tendon units. At the level of the quadriceps, the muscle-tendon units run all the way to the tibial tuberosity, and therefore include the patellar tendon. In other words, the patellar tendon is not modelled as a separate passive elastic element, but as an integral part of the muscle-tendon unit. The force transmission mechanism between the quadriceps and patellar tendon was modelled through fixed path points at the superior and inferior border of the patella (27). Motions of the 6 DoF trunk segment were driven by ideal torque actuators. Since no marker data from the arms were collected, the upper limb segments of the model were fixed in a typical running position: 0° of shoulder flexion, adduction, and internal rotation and 90° of elbow flexion and pronation. The spatial dimensions of the segments, the optimal muscle fibre lengths and tendon slack lengths in the generic model were scaled to the values of the individual participants using the marker data from a static calibration trial. The maximum isometric muscle forces were multiplied by three to avoid major reliance on reserve torque actuators during the fast concentric contractions that take place during running at high speed (30, 31). Joint kinematics during running were determined using a global optimisation approach, minimising the weighted sum of squared differences between the measured marker positions and the marker positions of the model (32). The movement of the patella was controlled by a spline function with the tibiofemoral flexion angle as a determinative variable. Net joint moments were calculated based on the kinematics results and the GRF data using the inverse dynamics tool. Forces of individual muscle-tendon units were calculated with a static optimisation approach (33). In this approach, the sum of the moments produced by the individual muscle-tendon units has to match the net joint moment for each frame and the sum of all muscle activations squared has to be minimal. To determine these muscle activations, the force-length and force-velocity relationships of the muscle-tendon units were taken into account. Finally, the kinematics, GRF, and muscle-tendon forces data were used to calculate joint reaction forces in the OpenSim joint reaction analysis tool (34).

Post-modelling processing was performed in Matlab R2020b (The MathWorks, Natick, MA, USA). The patellofemoral joint contact force was defined as the part of the total patellofemoral joint reaction force perpendicular to the patellofemoral joint surface. The PFJS was then calculated by dividing the patellofemoral joint contact force by the angle-specific patellofemoral joint contact area. This angle-specific contact area was determined using sex-specific regression functions created by Starbuck et al. (2021) (15) based on the MRI data of Besier et al. (2005) (35). PFJS values were expressed in megapascal (MPa). The PTF was defined as the force with which the patellar tendon pulls at the tibial tuberosity and was calculated as the scalar sum of forces produced by the four quadriceps muscle-tendon units. This simplification was possible since all muscle-tendon units of the quadriceps run in parallel at the level of the patellar tendon and insert at the tibial tuberosity. PTF was expressed in relation to the participants' body weight (BW). For each step, the peak PFJS and PTF were determined. Next, the peak rate of PFJS and PTF development and the PFJS and PTF impulse per step were determined using numerical differentiation and integration, respectively, of the PFJS-time curve and PTF-time curve. Finally, the PFJS and PTF impulse per km were calculated by multiplying the PFJS and PTF per step by the number of strides per km (36).

Statistical analysis

Peak load, peak rate of load development and load impulse per km were implemented in the statistical analysis. This statistical analysis was performed in the open-source software package SPM1D M0.4.9 (www.spm1d.org) (37). All load parameters investigated in this study were zero-dimensional. Two-way repeated measures ANOVA's were performed to assess the effect of running speed, step frequency and their interaction. Since normality tests showed that all parameters were not normally distributed, the non-parametric version of the repeated measures ANOVA based on the principle of permutation testing was chosen (38). Note, the a-priori sample size calculation was made under the assumption of a normal distribution of the data and consequentially parametric statistics. However, non-parametric permutation testing can be as powerful or sometimes even more powerful than parametric testing (38). The alpha value was set to 0.008.

In case of a significant effect in the repeated measures ANOVA, linear regression analyses were chosen as post-hoc analyses. The traditional paired t-test was not chosen as post-hoc analysis since a significant interaction effect in one parameter would result in a total of 105 paired t-tests. For each step frequency condition, a separate linear regression equation was generated with running speed as independent variable and the load parameter of interest as dependent variable. The regression coefficients represented the amount of increase or decrease in the load parameter with every 1km/h increase in running speed. In case of a significant main effect for running speed, the regression coefficients would be significantly different from zero, i.e. a horizontal line. The regression intercepts represented the values of the load parameter for the different step frequency conditions at a theoretical running speed of 0km/h. In case of a significant main effect for step frequency without interaction effect, the regression lines would be in parallel and the differences between the step frequency conditions, represented by the regression intercept, would be equal at every running speed. In case of a significant interaction effect, the regression coefficients would significantly different from one another and the regression lines would no longer be in parallel. Therefore, the differences in the load parameter between the step frequency conditions would be different at each running speed.

RESULTS

The data of one of the 13 participants were withdrawn from the statistical analysis because of technical issues during the data collection. The resulting 12 participants were 6 men and 6 women aged 22 ± 3 years, with a body mass of 68.5 ± 6.7kg, and height of 1.77 ± 0.10m (mean ± standard deviation). Absolute and relative values for the step frequencies at the different running speeds can be found in Table 1. The procedure aimed to increase or decrease the step frequency by 10%. Therefore, each relative frequency should ideally be 10 ± 0%. However, some variation in the step frequencies is visible. Next to the variation for each running speed, it is also important to know the within-subject variation in the context of a repeated measures design. The differences between the maximum and minimum step frequency were 4 ± 2% in both the increased and decreased condition. Information about other spatial-temporal parameters can be found in Supplemental Table 2 (see Supplemental Digital Content, Mean ± SD values for spatial-temporal parameters during the different running conditions, http://links.lww.com/MSS/C853).

Patellofemoral joint stress

Descriptive values for the PFJS load parameters can be found in Table 2 and Figure 1. For the peak PFJS, significant main effects were confirmed for running speed ($p<0.001$) and step frequency ($p<0.001$), with higher running speeds resulting in higher joint stress and higher step frequency in lower joint stress. There was no statistically significant interaction effect ($p=0.338$). The regression analysis of the peak PFJS showed separated parallel lines that increased similarly with increasing running speed. The regression coefficient for the habitual step frequency was 0.48MPa. For both the increased and decreased step frequency conditions, the regression coefficient was 0.38MPa. The increased step frequency condition decreased the peak PFJS, and conversely, the decreased step frequency condition increased the peak PFJS. The regression intercepts for habitual step frequency, increased step frequency and decreased step frequency were 3.65MPa, 2.96MPa and 5.85MPa, respectively.

The peak rate of PFJS development showed a significant main effect for running speed ($p<0.001$), a main effect for step frequency that tended towards statistical significance ($p=0.008$), but no significant interaction effect ($p=0.147$). The regression coefficients were 14.05MPa/s for habitual step frequency, 8.66MPa/s for increased step frequency and 15.40MPa/s for decreased step frequency.

For the PFJS impulse per km, significant main effects for running speed (p<0.001) and step frequency (p<0.001), and a significant interaction effect (p<0.001), were found. The regression analysis showed decreasing and converging lines as the running speed increased. The regression coefficients were −31.17MPa*s/km for habitual step frequency, −22.36MPa*s/km for increased step frequency and −36.86MPa*s/km for decreased step frequency. An increase in step frequency decreased the PFJS impulse per km and a decrease in step frequency increased the PFJS impulse per km. The regression intercepts were 796.25MPa*s/km for habitual step frequency, 635.35MPa*s/km for increased step frequency and 908.84MPa*s/km for decreased step frequency. However, the effect of step frequency alteration was larger at lower velocities compared to higher velocities.

Patellar tendon force

Descriptive values for the PTF load parameters can be found in Table 3 and Figure 2. Like the peak PFJS, the peak PTF revealed statistically significant main effects for running speed (p<0.001) and step frequency (p<0.001) without a significant interaction effect (p=0.376). Peak PTF increased with increasing running speed. The regression coefficients were 0.37BW for the habitual step frequency, 0.31BW for the increased step frequency and 0.30BW for the decreased step frequency. Regression intercepts altered between 2.13BW for the increased step frequency condition and 4.60BW for the decreased step frequency condition. The peak rate of PTF development showed a significant main effect for running speed (p<0.001). Peak rates of PTF development increased as running speed increased with the regression coefficient altering between 11.90BW/s and 15.04BW/s. In contrast to the PFJS, the peak rate of PTF development showed no main effect for step frequency (p=0.213). The interaction of running speed and step frequency was not statistically significant for the peak rate of PTF development (p=0.354). The regression lines were close together and increased with increasing running speeds. The PTF impulse per km showed a significant main effect for running speed (p<0.001), a significant main effect for step frequency (p<0.001) and a significant interaction effect between both factors (p<0.001). The PTF impulse per km decreased with increasing running speed. The regression coefficients were −24.03BW*s/km for habitual step frequency, −16.41BW*s/km for increased step frequency and −28.31BW*s/km for decreased step frequency. At low running speeds, the different step frequencies were separated. The highest regression intercept was detected at the decreased step frequency condition: 707.93BW*s/km. The lowest regression intercept of 485.21BW*s/km was detected at the increased step frequency condition. Towards 16km/h, the regression lines showed barely any difference between the step frequency conditions.

DISCUSSION

The objective of this study was to investigate whether the load-modifying effect of step frequency alterations was similar at different running speeds. Our hypothesis was partially confirmed: as the running speed increased, the effect of step frequency alterations on the impulse per km decreased. There was a large difference in the impulse per km between the step frequency conditions at lower running speed (8km/h), while the differences between the step frequency conditions were marginal at higher running speed (16km/h). This can be explained by the fact that increasing the step frequency does not automatically decrease the contact time with the same amount (see Supplemental Table 2, Supplemental Digital Content, Mean ± SD values for spatial-temporal parameters during the different running conditions, http://links.lww.com/MSS/C853). The step frequency can also be increased by reducing the flight time. Therefore, if the goal of altering the step frequency is to influence the cumulative load on the patellofemoral joint or the patellar tendon, the intervention might be more effective during slow jogging compared to high speed interval training. Future studies could even raise the question whether the effect might reverse and increasing the step frequency would increase the cumulative knee load when running speed is increased beyond 16km/h. This is well possible since earlier research from Dorn et al. (2012) investigating the transition from medium-paced to sprinting-paced running speeds, has shown changes in the behaviour of the different parts of the quadriceps (16). The force production of the rectus femoris during push-off and swing increased exponentially to increase the step frequency, while the force production of the vasti muscles during the breaking phase of stance reaches a steady state during sprinting because of the minimal ground contact time (16). All this will likely have an important effect on the PFJS-time and PTF-time curves and consequentially on the PFJS and PTF impulse per km.

The effect of step frequency alteration on peak PFJS and PTF was not influenced by running speed. Peak PFJS and PTF decreased by the same amount with increasing step frequency irrespective of the running speed. Furthermore, the peak PFJS and PTF increased with increasing running speed irrespective of the step frequency. These results are in agreement with previous studies indicating that peak knee load values increase with increasing running speed (14, 15, 39) and decrease when the step frequency is increased (12, 13, 20). Peak knee load values decrease at an increased step frequency because of a smaller peak knee flexion angle during stance and a smaller vertical excursion in the centre of mass, resulting in a reduced peak vertical GRF (18). Apparently, the rate with which these parameters change is not influenced by running speed. Peak rate of PFJS and PTF development only showed a significant increase with increasing running speed and was not significantly influenced by step frequency alterations. Since the sample size was calculated to reveal differences with a medium to large effect size, is possible that a difference with a small effect size may have remained unnoticed. Nevertheless, when the intention is to alter the peak rate of PFJS and PTF development, changing the running speed would be the preferred approach. We hypothesised that an interaction effect would be present in peak PFJS and PTF and peak rate of PFJS and PTF development since the combination of a higher running speed and a higher step frequency might form an incentive for the participants to change their running style, possibly including a shift from a heel strike pattern to a midfoot-forefoot strike pattern. Vannatta et al. (2015) demonstrated that female long-distance runners who changed their habitual rearfoot strike pattern for a forefoot strike pattern at running speeds of 3.52-3.89m/s (12.67-14.00km/h) significantly reduced their peak PFJS (40). However, Allen et al. (2016) showed already at habitual running speed that a 10% increase in step frequency is typically not enough to automatically change from a heel strike pattern to a midfoot-forefoot strike pattern (17). Additionally, in the study of Breine et al. (2014) only 36% of the 55 participants switched from a heel strike pattern to a midfoot-forefoot strike pattern when running speed was increased from 3.2m/s to 6.2m/s (11.52-22.32km/h) (41). Post hoc analysis of our data indicated that not a single participant altered their foot strike pattern throughout the different running speed and step frequency conditions (three of the 12 analysed participants ran consistently with a midfoot/forefoot strike pattern). Nevertheless, the interaction effect between foot strike pattern, running speed and step frequency on patellofemoral and patellar tendon load parameters can be an interesting topic for future research.

Some limitations in this study have to be reported. First, in the absence of devices that can measure PFJS or PTF directly in vivo in young, healthy individuals, musculoskeletal modelling was used to calculate these load parameters. Since a musculoskeletal model is an approximation and simplification, it comes with some assumptions and limitations. For example, not all muscle-tendon parameters of the model were scaled to subject-specific measures. This is because parameters like optimal fibre length and tendon slack length are difficult to scale accurately, even with advanced medical imaging (42). As a consequence, the maximum isometric muscle forces were set to three times the values of the generic model to guarantee sufficient muscle force during fast concentric contractions. Furthermore, patellofemoral contact areas were determined based on generic regression equations rather than individual medical imaging. Finally, the patellofemoral kinematics were controlled by a generic spline function, possibly missing patellofemoral maltracking (43). However, this study has a repeated measures design. Therefore, it could be argued that an error in the calculated load parameters was similar for all conditions within a participant and the statistical analysis was not affected as such. A second limitation is the step frequency alteration throughout the running protocol. Although a metronome is frequently used for step frequency alterations in running research (18), the method is not perfectly free from error. The predetermined percentage step frequency alteration was 10%. The fact that the average increase or decrease in step frequency for all participants was not always perfectly 10% for every running speed, probably influenced the effect size, but does not pose a threat to the main objective of the study. It is however questionable whether more familiarisation time would have reduced the variation in the step frequency. Running for one minute at each condition, and recording only the last 15 seconds, the participants had about 45 seconds to accommodate to each running condition. Whilst one may observe slowly continued adaptations in terms of running style after the initial accommodation to a condition, these would be expected to be very subtle. Additionally, more time at the higher running speeds could potentially generate more variation because of increased fatigue. A final limitation of this study is the absence of patients with patellofemoral pain syndrome or patellar tendinopathy. This study has included recreational runners, who have a higher risk of developing a running-related injury (44, 45). However, the recreational runners in this study were free of injury for at least six months. In patients with patellofemoral pain syndrome or patellar tendinopathy, a maladaptive running pattern might be the cause of the running-related injury. Conversely, pain might lead patients towards an altered running pattern that favours decreased knee loads. In these scenarios, this study might either under- or overestimate the effect of alterations in running speed or step frequency on PFJS and PTF parameters. However, previous studies did not find significant differences in PFJS between patients with patellofemoral pain syndrome and healthy individuals during running (13, 46).

Even in the absence of a patient group, this study has clinical implications. The results of this study can be used to develop a symptom modification test (18). First, the test could decide if maladaptive loading is a dominant factor for the development of patellofemoral pain syndrome or patellar tendinopathy. That is, if a patient can run a longer distance without pain in the patellofemoral joint or the patellar tendon if the running speed or the step frequency is altered, then load management may be considered as part of the rehabilitation. If the pain is not influenced by these alterations, other contributing factors and interventions need to be considered. Second, if maladaptive loading is a dominant factor and load management is considered as intervention, the test can help identify which load parameter should be controlled.

Namely, if a patient gets pain while running a certain distance at low speed, but not while running that same distance at high speed, the cumulative load is probably the dominant factor that causes the pain. This hypothesis can be confirmed when the pain disappears after an increase in step frequency at a low running speed. However, if a patient gets pain while running a certain distance at high speed but not while running that same distance at low speed, the peak load or peak rate of load development is probably the dominant factor that causes the pain. Since an increased step frequency at high speed significantly decreases the peak load, but not the peak rate of load development, step frequency alteration can be used to differentiate between both loading parameters as a dominant cause of pain. The exact running distance and running speed used during this symptom modification test, depend on the history of the individual patient in terms of habitual running parameters and the running distance and speed at which the pain is provoked. Furthermore, some patients may need a larger alteration in running speed and step frequency than others before the intervention becomes effective. Future studies with actual patients should confirm the effectiveness of this symptom modification test.

CONCLUSIONS

The load-reducing effect of increasing the step frequency on the impulse per km diminishes at faster running speed. Peak PFJS and PTF or peak rate of PFJS and PTF development per step increased with increasing running speed irrespective of the step frequency and the peak PFJS and PTF was reduced by increasing the step frequency, irrespective of the running speed. Clinicians can use this knowledge in their clinical examination to develop load management strategies for the treatment of patellofemoral pain syndrome and patellar tendinopathy.

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Conflict of Interest

The authors declare that there is no conflict of interest. The results of the present study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the study do not constitute endorsement by the American College of Sports Medicine.

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FIGURE LEGENDS

Figure 1 - Upper row: mean values of the PFJS -expressed in megapascal (MPa)- over time. Values are grouped according to running speed, combining all step frequencies (left) and according to step frequency, combining all running speeds (right). Lower row: regression lines peak PFJS (left), peak rate of PFJS development (middle) and PFJS impulse per kilometre (right). Red lines represent the increased step frequency condition, yellow lines the habitual step frequency condition and blue lines the decreased step frequency condition.

Figure 2 - Upper row: mean values of the PTF -expressed in bodyweight (BW)- over time. Values are grouped according to running speed, combining all step frequencies (left) and according to step frequency, combining all running speeds (right). Lower row: regression lines peak PTF (left), peak rate of PTF development (middle) and PTF impulse per kilometre (right). Red lines represent the increased step frequency condition, yellow lines the habitual step frequency condition and blue lines the decreased step frequency condition.

SUPPLEMENTAL DIGITAL CONTENT

SDC 1: Supplemental Digital Content.docx

Table S1 – Mean ± SD values for rate of perceived leg muscle exertion

Table S2 – Mean ± SD values for spatial-temporal parameters during the different running conditions

Figure 1

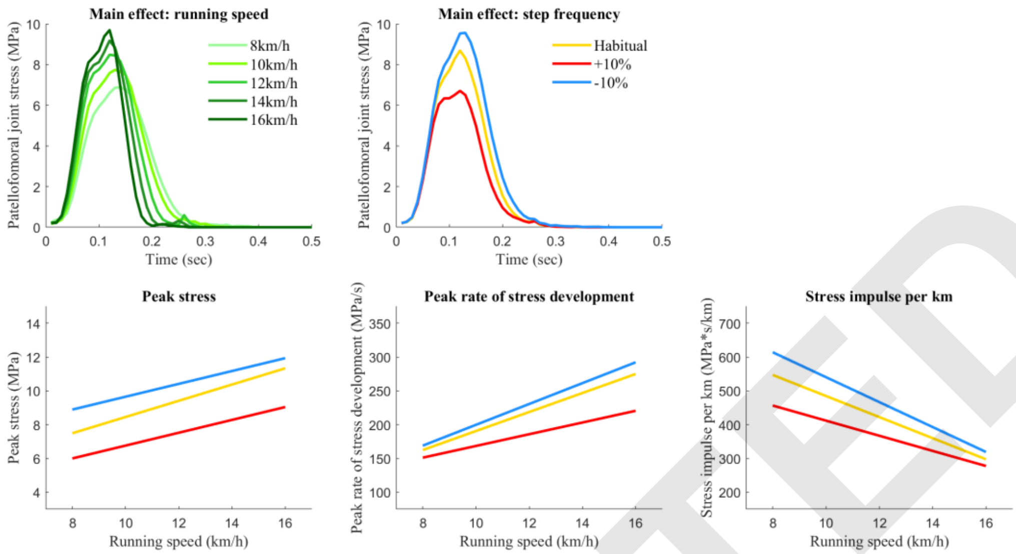
Main effect: running speed
Patellofomoral joint stress (MPa)
Time (sec)
8km/h
10km/h
12km/h
14km/h
16km/h
Main effect: step frequency
Patellofomoral joint stress (MPa)
Time (sec)
Habitual
+10%
-10%
Peak stress
Peak stress (MPa)
Running speed (km/h)
Peak rate of stress development
Peak rate of stress development (MPa/s)
Running speed (km/h)
Stress impulse per km
Stress impulse per km (MPa*s/km)
Running speed (km/h)

Figure 2

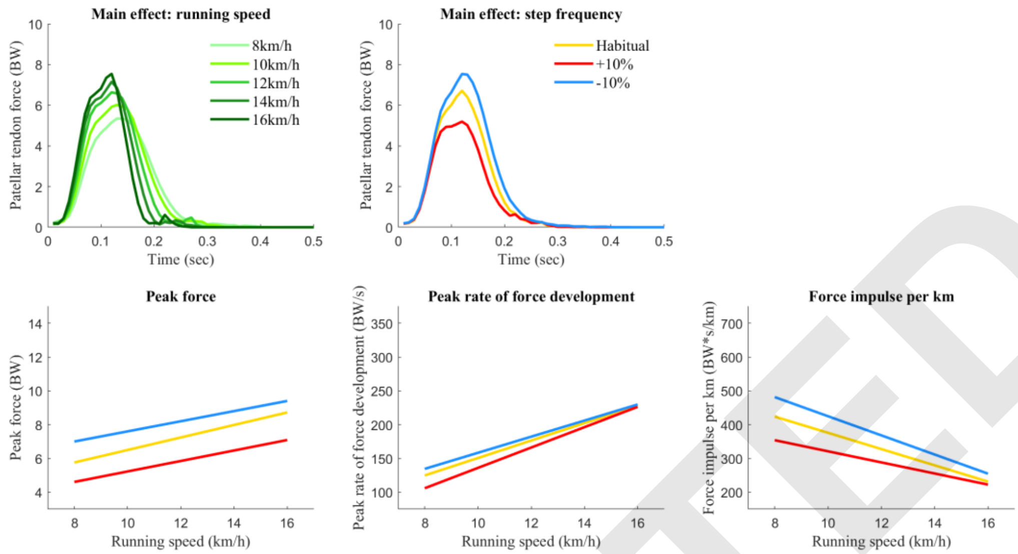
Main effect: running speed
Patellar tendon force (BW)
Time (sec)
8km/h
10km/h
12km/h
14km/h
16km/h
Main effect: step frequency
Patellar tendon force (BW)
Time (sec)
Habitual
+10%
-10%
Peak force
Peak force (BW)
Running speed (km/h)
Peak rate of force development
Peak rate of force development (BW/s)
Running speed (km/h)
Force impulse per km
Force impulse per km (BW*s/km)
Running speed (km/h)

Table 1. Mean ± SD values for the step frequencies at the different running conditions. The top values represent absolute values in steps per minute. The bottom values between brackets in the decreased and increased frequency condition represent relative percentages compared to the habitual frequency condition at the same running speed.

	Decreased frequency	Habitual frequency	Increased frequency
8km/h	145 ± 7 (-8 ± 3)	157 ± 7	173 ± 10 (10 ± 3)
10km/h	150 ± 7 (-7 ± 3)	161 ± 8	179 ± 9 (11 ± 2)
12km/h	155 ± 8 (-6 ± 4)	166 ± 9	184 ± 10 (11 ± 2)
14km/h	161 ± 10 (-6 ± 4)	171 ± 10	189 ± 13 (11 ± 3)
16km/h	169 ± 12 (-5 ± 3)	178 ± 12	196 ± 15 (10 ± 4)

Table 2. Mean ± SD values and results of the two-way repeated measures ANOVA and regression analyses for PFJS load parameters.

a) Peak PFJS

	Mean ± SD values (MPa)		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	8.63 ± 2.83	7.42 ± 2.21	5.97 ± 2.26
10km/h	9.86 ± 2.72	8.41 ± 2.67	6.92 ± 2.41
12km/h	10.54 ± 2.93	9.33 ± 2.63	7.56 ± 2.76
14km/h	11.28 ± 3.77	10.43 ± 2.78	8.25 ± 3.14
16km/h	11.72 ± 3.29	11.16 ± 3.31	9.15 ± 3.27
	Two-way repeated measures ANOVA		
	Running speed	**Step frequency**	**Speed*Frequency**
F-value	23.213	35.610	1.153
p-value	<0.001	<0.001	0.338
	Regression analysis		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
Coefficient	0.38	0.48	0.38
Intercept	5.85	3.65	2.96

b) Peak rate of PFJS development

	Mean ± SD values (MPa/s)		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	155.94 ± 40.79	147.55 ± 36.60	139.76 ± 36.27
10km/h	210.57 ± 72.53	192.62 ± 60.89	180.57 ± 54.95
12km/h	236.15 ± 83.50	241.21 ± 99.48	189.51 ± 65.66
14km/h	269.23 ± 113.07	255.09 ± 92.42	204.57 ± 61.59
16km/h	280.59 ± 84.49	256.83 ± 83.86	214.32 ± 58.77
	Two-way repeated measures ANOVA		
	Running speed	**Step frequency**	**Speed*Frequency**
F-value	14.857	5.797	1.558
p-value	<0.001	0.008	0.147
	Regression analysis		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
Coefficient	15.40	14.05	8.66
Intercept	45.71	50.04	81.87

c) PFJS impulse per km

	Mean ± SD values (MPa*s/km)		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	624.47 ± 215.21	563.11 ± 173.69	461.71 ± 179.04
10km/h	528.12 ± 169.76	470.14 ± 156.17	406.25 ± 150.28
12km/h	466.03 ± 112.12	411.02 ± 125.17	366.64 ± 122.04
14km/h	388.01 ± 98.54	361.11 ± 95.56	318.87 ± 102.12
16km/h	325.91 ± 78.20	305.97 ± 82.66	281.82 ± 80.78
	Two-way repeated measures ANOVA		
	Running speed	**Step frequency**	**Speed*Frequency**
F-value	34.951	53.670	7.490
p-value	<0.001	<0.001	<0.001
	Regression analysis		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
Coefficient	-36.86	-31.17	-22.36
Intercept	908.84	796.25	635.35

Table 3. Mean ± SD values and results of the two-way repeated measures ANOVA and regression analyses for PTF load parameters.

a) Peak PTF

	Mean ± SD values (BW)		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	6.77 ± 1.84	5.73 ± 1.48	4.58 ± 1.52
10km/h	7.77 ± 1.75	6.48 ± 1.76	5.34 ± 1.63
12km/h	8.31 ± 1.91	7.21 ± 1.71	5.87 ± 1.79
14km/h	8.85 ± 2.41	8.05 ± 1.76	6.42 ± 2.08
16km/h	9.22 ± 2.18	8.63 ± 2.14	7.16 ± 2.11
	Two-way repeated measures ANOVA		
	Running speed	**Step frequency**	**Speed*Frequency**
F-value	27.868	45.036	1.096
p-value	<0.001	<0.001	0.376
	Regression analysis		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
Coefficient	0.30	0.37	0.31
Intercept	4.60	2.80	2.13

b) Peak rate of PTF development

	Mean ± SD values (BW/s)		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	130.48 ± 36.27	123.57 ± 32.59	111.74 ± 27.33
10km/h	163.50 ± 45.13	148.55 ± 35.96	144.14 ± 42.29
12km/h	183.27 ± 46.91	185.87 ± 56.08	149.23 ± 46.03
14km/h	204.72 ± 65.57	194.49 ± 53.21	182.82 ± 46.59
16km/h	228.88 ± 62.20	229.57 ± 51.61	242.82 ± 82.96
	Two-way repeated measures ANOVA		
	Running speed	**Step frequency**	**Speed*Frequency**
F-value	32.256	1.686	1.124
p-value	<0.001	0.213	0.354
	Regression analysis		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
Coefficient	11.90	12.90	15.04
Intercept	39.37	21.64	-14.36

c) PTF impulse per km

	Mean ± SD values (BW*s/km)		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	488.76 ± 147.34	436.93 ± 121.91	357.49 ± 125.83
10km/h	414.78 ± 119.38	363.90 ± 108.80	315.55 ± 106.90
12km/h	370.90 ± 81.98	319.27 ± 88.05	290.49 ± 82.66
14km/h	307.47 ± 67.42	280.27 ± 65.12	253.22 ± 68.66
16km/h	259.34 ± 55.54	238.49 ± 54.17	224.52 ± 52.40
	Two-way repeated measures ANOVA		
	Running speed	**Step frequency**	**Speed*Frequency**
F-value	31.785	68.768	7.994
p-value	<0.001	<0.001	<0.001
	Regression analysis		
	Decreased frequency	**Habitual frequency**	**Increased frequency**
Coefficient	-28.31	-24.03	-16.41
Intercept	707.93	616.08	485.21

Supplemental Table 1. Mean ± SD values for rate of perceived leg muscle exertion. The top values represent absolute values on the CR100 scale. The bottom values between brackets in the decreased and increased frequency condition represent relative percentages compared to the habitual frequency condition at the same running speed.

	Decreased frequency	Habitual frequency	Increased frequency
8km/h	5 ± 7 (0 ± 3)	5 ± 7	5 ± 6 (0 ± 2)
10km/h	9 ± 10 (-1 ± 4)	10 ± 11	11 ± 9 (1 ± 5)
12km/h	21 ± 17 (1 ± 8)	20 ± 15	22 ± 13 (2 ± 9)
14km/h	34 ± 21 (-2 ± 16)	36 ± 20	38 ± 17 (2 ± 14)
16km/h	46 ± 22 (-6 ± 12)	52 ± 21	53 ± 20 (1 ± 15)

Supplemental Table 2. Mean ± SD values for spatial-temporal parameters during the different running conditions.

a) Contact time (s)

	Decreased frequency	**Habitual frequency**	**Increased frequency**
8km/h	0.33 ± 0.04	0.31 ± 0.03	0.29 ± 0.03
10km/h	0.29 ± 0.02	0.28 ± 0.02	0.27 ± 0.03
12km/h	0.26 ± 0.02	0.25 ± 0.02	0.24 ± 0.02
14km/h	0.24 ± 0.02	0.24 ± 0.02	0.23 ± 0.02
16km/h	0.22 ± 0.01	0.22 ± 0.01	0.21 ± 0.02

b) Stride length (m)

	Decreased frequency	Habitual frequency	Increased frequency
8km/h	0.33 ± 0.04	0.31 ± 0.03	0.29 ± 0.03
10km/h	0.29 ± 0.02	0.28 ± 0.02	0.27 ± 0.03
12km/h	0.26 ± 0.02	0.25 ± 0.02	0.24 ± 0.02
14km/h	0.24 ± 0.02	0.24 ± 0.02	0.23 ± 0.02
16km/h	0.22 ± 0.01	0.22 ± 0.01	0.21 ± 0.02

c) Strides per km

	Decreased frequency	Habitual frequency	Increased frequency
8km/h	528 ± 63	595 ± 27	655 ± 37
10km/h	431 ± 46	480 ± 23	533 ± 28
12km/h	409 ± 68	418 ± 23	485 ± 86
14km/h	364 ± 55	374 ± 23	429 ± 68
16km/h	330 ± 47	337 ± 22	383 ± 61