PREDICTORS OF PELVIC ACCELERATION DURING TREADMILL RUNNING AT DIFFERENT STRIDE FREQUENCIES

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The aim of this study was to examine predictors of peak vertical and anteroposterior pelvic acceleration during treadmill running. Participants ran at 9 km·h^{-1} at their preferred stride frequency and at ± 5% of their preferred stride frequency. Coordinate and acceleration data were collected using a motion capture system and inertial measurement units. Linear mixed models showed that for every one standard deviation increase in the anteroposterior displacement from knee to ankle at initial contact, vertical pelvic acceleration increased by 2.18 m·s^{-2} (p = 0.046). Additionally, for every one standard deviation increase in stride frequency, peak anteroposterior pelvic acceleration increased by 0.68 m·s^{-2} (p = 0.035). Runners who suffer from injuries or pain at the pelvis may benefit from decreasing the anteroposterior displacement from their knee to their ankle at initial contact and reducing their stride frequency.

KEYWORDS: tibial acceleration, contact time, stiffness

INTRODUCTION: Running has many health benefits, yet it is also associated with a risk of overuse injuries. Overuse injuries can often occur at the pelvis (Taunton et al., 2002). Since the pelvis is loaded twice during a stride, it is repeatedly exposed to high forces, increasing the odds of musculoskeletal injuries (Gallagher et al., 2013). Quantifying the mechanical loading of the pelvis and predictors of such loading may identify risk factors for pelvis-related injuries. However, to date more is known about lower limb loading than pelvis loading.
Lower limb running-related injuries are associated with high peak vertical and horizontal forces, as well as tibial loading quantified using tibial acceleration (Milner et al., 2006; Napier et al., 2018). Reducing these biomechanical lower limb injury risk factors through running gait retraining can be effectively done by increasing stride frequency (Busa et al., 2016; Napier et al., 2018). Theoretically, manipulating stride frequency may also assist in changing pelvic load given the known changes to ground reaction forces and tibial acceleration, but research is needed to confirm this hypothesis.
Several changes to running gait occur when stride frequency is manipulated. Specifically, increasing stride frequency reduces tibial acceleration, braking and vertical impact forces and vertical centre of mass displacements (Busa et al., 2016; Napier et al., 2018; Morin et al., 2007). These changes would reduce the force that needs to be dissipated by proximal structures, which may in turn decrease pelvic load. Additionally, higher stride frequencies are often associated with greater knee flexion at initial contact, as well as reductions in contact time (Heiderscheit et al., 2011; Morin et al., 2007). These alterations may also affect pelvic loading through changes in ground reaction forces. For example, landing with a greater anteroposterior displacement from the knee to the foot, indicative of greater knee flexion, has been positively associated with vertical peak impact forces (Lieberman et al., 2015), whereas a greater displacement from the hip to ankle has been associated with increased peak braking forces (Lieberman et al., 2015). A lower contact time will reduce the amount of time for production of the forces required to maintain speed, which may then affect the magnitude of impact force peak (Morin et al., 2007).
Understanding predictors of vertical and anteroposterior pelvic acceleration, will potentially aid in development of gait retraining interventions to decrease running pain or injuries at this region. This study aimed to assess whether tibial acceleration, lower limb kinematics, stride frequency and contact time predicted vertical and anteroposterior peak pelvic acceleration during treadmill running.

METHODS: Ten healthy runners (6 female, age: 29.0 ± 6.2 years, mass: 65.6 ± 19.8 kg, height: 1.69 ± 0.10 m), varying from recreational to elite level, participated in the study. Participants had no history of anterior knee pain, current lower-limb injuries, neurological impairments or cardiovascular pathologies.

Three, one-minute trials were performed at 9 km·h^{-1}. Conditions were randomised and consisted of preferred stride frequency and ± 5% of this preferred stride frequency. Stride frequency was dictated by an audible metronome beat. Data were collected using a motion capture system (200 Hz), with reflective markers placed on the left lower limb and triaxial accelerometers placed on the pelvis and tibia (225 Hz). Video data (100 Hz), synched with the motion capture system, were also captured in the sagittal plane allowing touchdown and toe-off events to be identified and digitised. None of the ± 5% of preferred stride frequency trials exhibited less than a 4% change from the preferred stride frequency condition. Coordinate and tibial acceleration data were filtered with a low-pass, fourth order Butterworth filter, with cut-off frequencies of 13 Hz and 70 Hz respectively, determined via residual analysis (Winter, 2009). The pelvic acceleration filtering cut-off frequency was 10 Hz (Day et al., 2021). A custom Matlab code (MATLAB, Mathworks Inc., Natick, MA, USA) based on previous methods (Moe-Nilssen, 1998) aligned the acceleration data to global axes.

Mean vertical peak positive and anteroposterior (AP) peak negative pelvic and tibial acceleration (m·s^{-2}) for the last ten left stance phases of each trial were identified. The AP displacements (cm) from the knee and hip to the ankle, at the corresponding touch downs were also measured and contact time was determined by the time between touchdown and subsequent toe-off events.

Two linear mixed models assessed predictors of pelvic acceleration using z-scored data. “Participant” was used as a random grouping effect to account for repeated measures, addressing the issue of independence of observations, and predictor variables were entered as fixed effects. Models used maximum likelihood estimation and statistical significance was accepted at alpha level 0.05. Analysis was undertaken in the statistical package R.

RESULTS: From the lowest stride frequency to the highest, stride time decreased from 0.78 to 0.71 s. In addition, vertical pelvic acceleration decreased whilst in the AP direction it increased (Table 1). Additionally, there was only a small decrease in contact time and displacement from hip to ankle, with largest reductions observed in vertical tibial acceleration (Table 1). Displacement from knee to ankle and AP tibial acceleration showed inconsistent changes.

Table 1. Group means ± standard deviations of model variables for each stride frequency condition. A positive displacement from the knee to ankle indicates the ankle is anterior to the knee. AP denotes anteroposterior.

Variable	Stride frequency condition		
	–5%	Preferred	+5%
Stride frequency (Hz)	1.28 ± 0.06	1.34 ± 0.06	1.41 ± 0.07
Contact time (s)	0.30 ± 0.03	0.29 ± 0.02	0.28 ± 0.01
Vertical pelvic acceleration (m·s^{-2})	25.22 ± 3.98	25.19 ± 4.60	23.97 ± 4.53
Vertical tibial acceleration (m·s^{-2})	58.57 ± 25.80	55.00 ± 28.13	52.97 ± 25.47
Displacement from knee to ankle (cm)	–0.04 ± 2.37	0.21 ± 2.98	–0.74 ± 2.59
AP pelvic acceleration (m·s^{-2})	–7.36 ± 2.76	–7.78 ± 3.16	–8.58 ± 3.62
AP tibial acceleration (m·s^{-2})	–59.27 ± 31.32	–61.90 ± 25.38	–58.83 ± 29.03
Displacement from hip to ankle (cm)	16.82 ± 2.34	16.67 ± 1.91	15.34 ± 1.54

For every one standard deviation increase in the anteroposterior displacement from the knee to the ankle there was a 2.18 m·s^{-2} increase in vertical pelvic acceleration ($p = 0.046$; Table 2). Meanwhile, for every one standard deviation increase in stride frequency there was a 0.68 m·s^{-2} increase in magnitude of AP pelvic acceleration ($p = 0.035$; Table 2). There were no other predictors of vertical or AP pelvic acceleration ($p > 0.05$; Table 2).

Table 2. Linear mixed model (LMM) outcomes for predicting peak positive vertical and peak negative anteroposterior (AP) pelvic acceleration. A positive displacement from the knee to ankle indicates the ankle is anterior to the knee.

LMM	Dependent Variable	Fixed Factors	Co-efficient (standard error)	*t*-value	*p*-value
1	Vertical pelvic acceleration	Vertical tibial acceleration	–0.145 (0.913)	–0.159	0.876
		Displacement from knee to ankle	2.179 (1.031)	2.115	0.046*
		Stride frequency	–0.546 (0.762)	–0.717	0.480
		Contact time	–0.283 (0.918)	–0.308	0.760
2	AP pelvic acceleration	AP tibial acceleration	–0.622 (0.530)	–1.174	0.253
		Displacement from hip to ankle	–0.190 (0.344)	–0.552	0.587
		Stride frequency	–0.677 (0.297)	–2.277	0.035*
		Contact time	0.263 (0.468)	0.562	0.580

*Significant at 0.05 level.

DISCUSSION: This study examined whether tibial acceleration, lower limb kinematics, stride frequency and contact time predicted vertical and AP peak pelvic acceleration during treadmill running. An increase in AP displacement from the knee to the ankle predicted an increase in peak vertical pelvic acceleration, meanwhile, increased stride frequency predicted an increase in peak AP pelvic acceleration magnitude.

The larger displacement from the knee to the ankle may indicate greater knee extension was present, as the shank would need to be rotated further backwards. Additionally, only minimal changes to contact time (2 ms) occurred across the stride frequency conditions compared to stride time (7 ms). This indicates that higher pelvic accelerations, occurring at lower stride frequencies, had lower duty factors. Low duty factors are accompanied by greater knee extension (Patoz et al., 2020). The potentially greater knee extension present may reduce the lower limb’s capacity to attenuate force and increase pelvic loading (Hamill et al., 2009; Lieberman et al., 2015). Consequently, encouraging runners with pelvic pain to reduce knee extension at initial contact may facilitate reductions in pelvic loading.

The finding that a higher stride frequency predicted greater magnitudes of AP pelvic acceleration contrasts with findings observed in relation to peak braking force and braking impulse (Heiderscheit et al., 2011; Napier, et al., 2018). This suggests that assuming pelvic related accelerations represent the centre of mass forces, as quantified using a force plate should be done with caution. Our data shows the pelvis undergoes rapid AP deceleration upon initial contact, and this was not predicted by AP tibial deceleration, hip to ankle displacement or contact time. Similarly to vertical pelvic acceleration, duty factor may play a role. Specifically, higher duty factors that likely accompanied the higher stride frequencies promote forward propulsion over vertical oscillation (Patoz et al., 2020). However, the stride frequency manipulations used in the current study produced smaller acceleration changes than previous studies, potentially due to only using a 5% increase or decrease in preferred stride frequency (Mercer et al., 2003). Characterising the biomechanical changes over a larger range of stride frequencies manipulations may provide further understanding and should be explored in future. Additionally, exploring vertical and AP pelvic acceleration with a group of runners suffering pelvic pain is needed to ascertain, which component may be the most influential on pain.

The limited predictor variables identified in this study indicates that a combination of strategies may be employed by individuals in the production of pelvic acceleration. Additionally, the multifaceted and complex nature of overuse injuries (van Poppel et al., 2021) may mean that predictor variables need to be considered in conjunction with other factors, rather than independently, when assessing injury risk. Further research should include a larger sample and more extreme range of stride frequency conditions, as well as sub-group analysis, for example between males and females, to examine predictors more closely in different populations.

CONCLUSION: This study found that increasing anteroposterior displacement from the knee to the ankle when landing and increasing stride frequency predicts an increased vertical and anteroposterior pelvic acceleration, respectively. This indicates that decreasing this distance, via an increase in knee flexion, and reducing stride frequency, may reduce load on the pelvis and be beneficial for runners suffering from pelvic pain and injuries. As an increased knee flexion is commonly reported during faster stride frequencies, the findings represent an opposition in strategies. This emphasises the necessity to assess both vertical and anteroposterior pelvic acceleration, as assessment of one component may recommend a strategy that, in isolation, is detrimental to the other.

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