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Short communication

Force measurements during running on different instrumented treadmills



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ABSTRACT

One method to determine the forces produced during running is to conduct extensive kinematic and kinetic analysis. These analyses can be performed by having an individual perform repeated over-ground running trials or simply run continuously on an instrumented treadmill. The forces produced during over-ground running may not be the same as the forces during treadmill running and these differences could be attributed to a number of factors, including the design of the instrumented treadmill. The purpose of this paper was to determine whether there are differences in force measurements on different instrumented treadmill setups in comparison to over-ground running and to correct for any of these differences using a theoretical model. 11 participants ran on three different treadmills and performed over-ground running at 2.7, 3.6, and 4.5 m/s. Ground reaction forces were measured via force plates and an instrumented pressure insole. We found that the magnitude of the vertical ground reaction force differed between the three treadmills and over-ground running. The difference in ground reaction forces estimated by the pressure insole and the treadmill-force-plate system or instrumented treadmill can be explained by a three degree of freedom mechanical model of a person running on a treadmill and this model could potentially be used to correct for errors in force measurement from instrumented treadmills. The model included a force plate, a treadmill, and a wobbling mass with varying natural frequencies and damping characteristics, and constant masses. These findings provide researchers a method to correct forces from an instrumented treadmill set-up to determine a close approximation of the actual forces experienced by a participant during treadmill running.

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1. Introduction

The use of instrumented treadmills in gait research has grown substantially (Bredeweg et al., 2013; Item-Glatthorn et al., 2016; Kram and Powell, 1989). Since instrumented treadmills are frequently used in gait research, it begs the question whether treadmill gait is similar to over-ground running/walking. To date, this topic is inconclusive (García-Pérez et al., 2013; Kluitenberg et al., 2012; Nigg et al., 1995; Riley et al., 2008; Sinclair et al., 2013; Watt et al., 2010). Force differences reported during treadmill and over-ground running (Belli et al., 2001; Dierick et al., 2004; Gosse et al., 2010; Kram et al., 1998), particularly force oscillations,

could be driven by the specific design of the instrumented treadmill. Specifically, different materials with different stiffness and damping properties in the treadmill could affect the recorded force from the measurement system and the force that is applied to the human body (i.e., the foot). Further, the recorded forces could change differently depending on the running speed of the person. No research, however, has systematically examined the effects of different instrumented treadmill set-ups on the recorded ground reaction force during gait.

The primary purpose of this study was to determine whether ground reaction forces recorded from different instrumented treadmill set-ups (expensive and inexpensive) are comparable to the forces that are actually acting on the human body (i.e., foot). To further support the primary purpose of the paper, there were additional secondary purposes of this study which were to (A) compare the instrumented treadmill forces to over-ground

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running, (B) compare changes in recorded forces as a function of running speed, and (C) use a theoretical model to explain any observed differences in the ground reaction forces as estimated by the pressure insole and the treadmill-force-plate system or instrumented treadmill. The null hypotheses are that:

H1: The forces recorded across the different instrumented treadmill set-ups would produce the same forces and would also be the same as over-ground running

H2: The forces recorded by an insole pressure measurement system would be the same when running on different treadmills or over-ground.

2. Methods

2.1. Participants and protocol

Eleven recreational runners (7 males, 4 females, age, 26 ± 2 yr, body weight, 70.3 ± 8.7 kg, height 174.0 ± 7.4 cm) who ran between 1 and 4 times per week provided written, informed consent to participate in this study. The study was approved by the University of Calgary's Conjoint Health Research Ethics Board, in accordance to the Declaration of Helsinki. Participants completed running trials at three different speeds (i.e., 2.7, 3.6, and 4.5 m/s; 30 s) on three different treadmills (Quinton Q65 research treadmill [Quinton Instrument Co., Seattle, WA, USA], Healthrider H20T [ICON Health & Fitness, Logan, UT, USA] and Bertec [Bertec, Columbus, OH, USA]) and during over-ground running (5 trials) in their own running shoes. These speeds were based on previous research (Bailey et al., 2017; García-Pérez et al., 2013; Sinclair et al., 2013) and the fact that these speeds cover the range of speeds typically offered by publicly available commercial treadmills. The Bertec was assumed to be the stiffest and there were differences in the stiffness characteristics of the other two treadmills as shown by an experimental modal analysis (Supplementary Table 1).

2.2. Measurements and data processing

During each running trial, there were two main measurements – the ground reaction force and the summed pressure from an instrumented insole. The ground reaction force was measured from force plates (Kistler Instrumente AG, Switzerland) at a sampling rate of 2400 Hz for the over-ground running (one force plate) and two treadmill conditions (2 force plates; Quinton, Healthrider). The Bertec treadmill measured ground reaction force with embedded force transducers underneath the treadmill surface. The second measurement was the force from an instrumented insole. The total force acting on the right foot was determined by the summed (i.e., discrete integral) pressure distribution across 99 cells, multiplied by each cell's area, with an instrumented insole at 200 Hz (Pedar-X; Novel, Germany). The pressure insole was placed on top of the shoe insole and the experimenter checked to ensure the pressure insole provided full coverage inside the shoe. The same 5 trials were analyzed for the force platform and instrumented insole data, 5 being a typical number of ground contacts analyzed when comparing treadmill and over-ground running (Fellin et al., 2010).

2.3. Three-degree of freedom model

We assume that the force recorded by the insole pressure system was a close approximation to the “true” input for a three-degree-of-freedom (3 DOF) linear system of masses, springs and dampers (Fig. 2). The model is aimed at showing that the force recorded by a force plate placed underneath a treadmill is very different from the “true” ground reaction force as measured by the insole pressure system.

The masses are denoted by the indices 1, 2, 3:

1. the ensemble of the two force plates on which the treadmill rests,
2. the frame of the treadmill,
3. a wobbling mass, representing the components of the treadmill that vibrate within the treadmill.

The governing equation of this system is

$$[M]\{\ddot{x}(t)\} + [R]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\} \quad (1)$$

where $\{x(t)\}$ is the 3×1 vector of the displacements given by

$$\{x(t)\}^T = [x_1(t) \quad x_2(t) \quad x_3(t)] \quad (2)$$

and $\{F(t)\}$ is the 3×1 vector of the external forces, given by

$$\{F(t)\}^T = [F_1(t) \quad F_2(t) \quad F_3(t)] = [0 \quad -F_{ps}(t) \quad 0] \quad (3)$$

in which the only non-zero force is that applied on the treadmill (mass 2), given by the negative of the force $F_{ps}(t)$ measured by the pressure system. The matrices

$$[M] = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix},$$

$$[R] = \begin{bmatrix} r_1 + r_2 & -r_2 & 0 \\ -r_2 & r_2 + r_3 & -r_3 \\ 0 & -r_3 & r_3 \end{bmatrix},$$

$$[K] = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix},$$
(4)

are the 3×3 mass, damping and stiffness matrices, respectively. The stiffnesses k_i are defined in terms of the corresponding free, non-damped angular frequencies ω_{0i} (we recall that the angular frequency is defined as $\omega = 2\pi f$, f being the frequency), i.e. (no sum with respect to index i),

$$k_i = m_i \omega_{0i}^2, \quad (5)$$

Analogously, the damping coefficients r_i are defined in terms of the corresponding characteristic times τ_i , i.e. (no sum with respect to index i),

$$r_i = \frac{2m_i}{\tau_i}. \quad (6)$$

We set the initial conditions as

$$\{x(0)\}^T = [000], \quad \{\dot{x}(0)\}^T = [000], \quad (7)$$

i.e., all initial displacements and velocities are set to zero.

Since the coordinates x_i were taken positive if upwards, and all forces of interest are downwards, in order to obtain positive values, we define the force measured by the force plate by

$$F_{fp}(t) = -[r_2(\ddot{x}_2(t) - \dot{x}_1(t)) + k_2(x_2(t) - x_1(t))]. \quad (8)$$

3. Data analysis

The main dependent measure for the experimental data was the peak of the vertical ground reaction force. The average of 5 peaks for each participant across each running condition (i.e., 3 treadmills and over-ground running) and speed (3 speeds) was used for data analysis. To statistically compare whether the peak vertical ground reaction force was different across the running

conditions and if these differences were dependent on speed, we conducted a 4×3 repeated-measures ANOVA (4 running conditions: Quinton treadmill, Healthrider treadmill, Bertec treadmill, over-ground running; 3 running speeds: 2.7, 3.6, and 4.5 m/s). This analysis was conducted with the pressure insole measurement data and the force plate or instrumented treadmill data. The *F*-statistic, *p*-value, and eta-squared values are presented.

4. Results

The ANOVA revealed an interaction effect between running condition and speed ($F_{(3,016,30.161)} = 7.593, p = 0.001, \eta^2 = 0.012$) and main effects for speed ($F_{(1,157,11.566)} = 109.833, p = 0.001, \eta^2 = 0.0178$), and running condition ($F_{(3,30)} = 59.998, p = 0.001, \eta^2 = 0.413$) for the peak vertical ground reaction force. The results from the post-hoc analysis are presented in Table 1. The ANOVA for the pressure measurement system revealed no significant interaction ($F_{(6,60)} = 1.488, p = 0.198, \eta^2 = 0.006$), a main effect for the running speeds ($F_{(1,275,12.754)} = 104.702, p < 0.001, \eta^2 = 0.262$), and the main effect for running condition was not significant ($F_{(3,30)} = 2.355, p = 0.092, \eta^2 = 0.025$). The effect sizes reveal that the explained variance was primarily due to the running condition for the force plate or instrumented treadmill recordings, while for the pressure measurement system, the running speed was the largest contributor to the explained variance. Table 1 reports the impact peaks of the vertical ground reaction force for four running conditions that were recorded on the force plate and the pressure measurement system.

Fig. 1A show the forces traces for one representative subject running on the Quinton treadmill, while Fig. 1B shows the force traces while running on the Healthrider treadmill.

The force traces from the force plate versus the instrumented insole are different for the Quinton and Healthrider (Fig. 1A and B). For the Bertec treadmill and over-ground running, however, these force traces are similar (Fig. 1C and D). When examining

the insole pressure system across the different running conditions of a representative participant, it is evident that these forces are quite similar. The next two sections propose a theoretical model to explain these force differences, particularly for two of the treadmills (Quinton, Healthrider).

5. Mechanical model results

In our numerical tests, we kept all masses constant and performed a sensitivity analysis on several parameters. The two parameters with the largest influence on the tests were the stiffness k_3 of the wobbling mass and the damping coefficient r_2 of the treadmill, while the damping coefficient r_3 of the wobbling mass has a relatively small effect. Therefore, we performed a parametric analysis by varying $k_3 = m_3\omega_{03}^2$ and $r_2 = 2m_2/\tau_2$ and found that two extreme values of r_2 are able to model the Quinton and the Healthrider treadmills. The specific values of the force plate, treadmill, and wobbling mass are presented in Table 2.

The system was solved numerically with Mathematica (Wolfram Research, Champaign, Illinois, USA). The force $F_{fp}(t)$ of the force plate is plotted in Fig. 3A for $\tau_2 = 0.5$ s (similar to the Quinton treadmill) and parametric values of ω_{03} , while Fig. 3B shows the plot of $\tau_2 = 0.005$ s (similar to the Healthrider treadmill) and parametric values of ω_{03} . For lack of knowledge of the values of these parameters, we selected those values that, after many iterations of the model, best fit the experimental data presented.

Fig. 3 shows that, for the chosen, plausible values of the involved parameters, the simulated force measured by the force plate reproduces those obtained with the Quinton and Healthrider setups, respectively. Note that, in order to make a direct comparison, we used the same pressure system force as the input, specifically, that measured with the Quinton setup. We can conclude that the wobbling parts of the treadmill as well as the damping coefficient of the treadmill can have an influence on the measurements made by means of force plates. By “damping of

Table 1

Differences of impact peaks from the force trace when running on the different treadmills or over-ground with *p* values presented in the table cells. The lower table indicates the group mean (SD) impact peak force recorded on the force plate [N] and the pressure measurement system [N]. The table displays that the mean peak of the ground reaction forces across running conditions on the treadmill are much greater than the differences recorded from the insole pressure measurement system.

6 mph	Quinton		Healthrider		Bertec		Overground	
Quinton	–		$p < 0.001$		$p < 0.001$		$p < 0.001$	
Healthrider	–		–		$p = 0.110$		$p = 0.028$	
Bertec	–		–		–		$p = 0.066$	
Overground	–		–		–		–	
8 mph	Quinton		Healthrider		Bertec		Overground	
Quinton	–		$p < 0.001$		$p < 0.001$		$p < 0.001$	
Healthrider	–		–		$p = 0.325$		$p = 0.016$	
Bertec	–		–		–		$p = 0.105$	
Overground	–		–		–		–	
10 mph	Quinton		Healthrider		Bertec		Overground	
Quinton	–		$p < 0.001$		$p < 0.001$		$p < 0.001$	
Healthrider	–		–		$p = 0.128$		$p = 0.002$	
Bertec	–		–		–		$p = 0.029$	
Overground	–		–		–		–	
Condition	Healthrider		Bertec		Quinton		Overground	
	Insole	Force Plate						
6 mph	1026 (2 89)	1156 (2 27)	965 (2 38)	1077 (2 33)	935 (2 19)	1642 (3 80)	862 (2 26)	990 (2 4 3)
8 mph	1128 (2 03)	1368 (2 61)	1121 (2 72)	1301 (3 17)	1115 (2 30)	2027 (5 10)	1051 (2 06)	1176 (2 03)
10 mph	1315 (2 45)	1656 (3 14)	1361 (3 31)	1551 (3 65)	1257 (2 26)	2376 (5 19)	1232 (1 92)	1359 (2 00)
Average	1156	1393	1149	1310	1102	2015	1048	1175

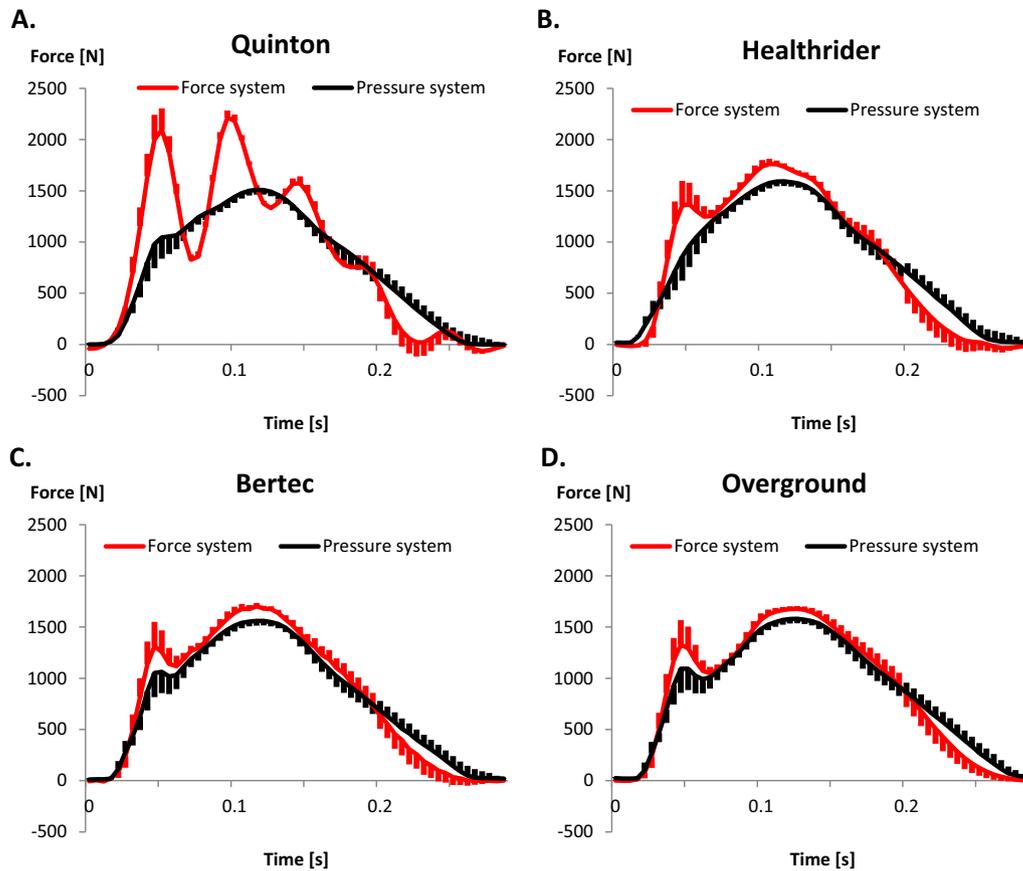


Fig. 1. All ground reaction force figures are from one representative subject. A: The average force trace (\pm SD) recorded from a representative subject running on the Quinton treadmill. Force traces were averaged across 5 steps and recorded from the force plate and the pressure measurement system placed in the insole of the shoe. B: The average force trace (\pm SD) recorded from a representative subject running on the Healthrider treadmill. Force traces are were averaged across 5 steps and recorded from the force plate and the pressure measurement system placed in the insole of the shoe. C: The average force trace (\pm SD) recorded from a representative subject running on the Bertec treadmill. Force traces are were averaged across 5 steps and recorded from the treadmill's force transducers and the pressure measurement system placed in the insole of the shoe. D: The average force trace (\pm SD) recorded from a representative subject running over-ground. Force traces are were averaged across 5 steps and recorded from the force plate and the pressure measurement system placed in the insole of the shoe.

Table 2

Values of the parameters of the 3 DOF system. The values for the mass and frequency of the force plate are taken from the specifications from Kistler (Winterthur, Switzerland).

	Mass m_i [kg]	Frequency ω_{0i} [s^{-1}]	Time constant τ_i [s]
1. Force plate	45	500	0.5
2. Treadmill	75	120	par.: (0.005; 0.5)
3. Wobbling part	25	par.: (10, 100, 1000)	0.1

the treadmill”, we mean any source of damping from the frame of the treadmill, which include the feet of the treadmill (arguably the most damping elements).

Remark. Another possible strategy for analysis may be to consider the force plate reading as the model's input and to evaluate the pressure system reading from the model and then compare it to the experimental result. We have attempted this route and obtained a system of differential algebraic equations (DAE), which are known to be strongly dependent on the initial conditions and do not generally admit solutions for an arbitrary set of initial conditions.

6. Discussion

The primary purpose of this study was to determine whether ground reaction forces recorded from different instrumented

treadmill set-ups are comparable to the forces that are actually acting on the human body. H1 was partially supported. The forces recorded on the force plate were different across the three treadmill conditions, but it was dependent on the running speed. The older research treadmill produced different forces compared to the other treadmill conditions and over-ground running when other factors were controlled (i.e., speed). H2 was not supported. The insole pressure measurement system showed that the forces increase when running speed increases while controlling all other factors; the running condition is not statically associated with the forces according to the IPMS after accounting for other influential variables (i.e., running condition).

The experimental results indicated that the vertical ground reaction forces recorded from the force plate were much greater than those recorded by the insole pressure measurement system. One might assume that to calculate the ground reaction force experienced by the runner, a researcher could simply record the ground reaction force by placing a treadmill on top of force plates. This set-up of placing the treadmill on the force plate would not represent the actual force acting on the participant, unless one adjusts its results, e.g., by means of the presented three-degrees-of-freedom model. We have provided a plausible explanation for the discrepancy between the ground reaction forces recorded from the two measurement systems using this model (i.e., insole vs. force plate).

By means of this model, we were able to recreate features of the experimental results. Specifically, we were able to reproduce the

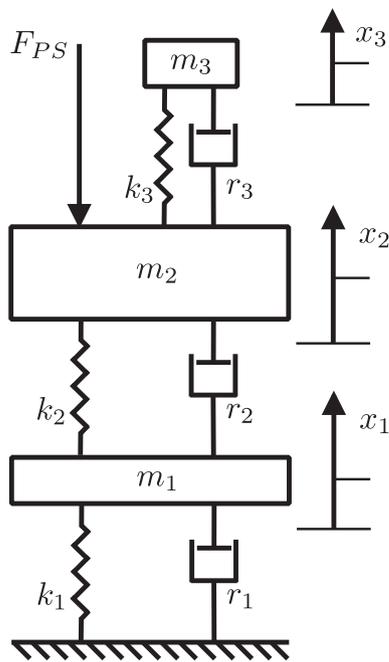


Fig. 2. A free body diagram of a person running on a treadmill. A 3 DOF system that models a person running on a treadmill on top of a force plate with m_1 representing the force plate, m_2 representing the treadmill, and m_3 representing the wobbling mass.

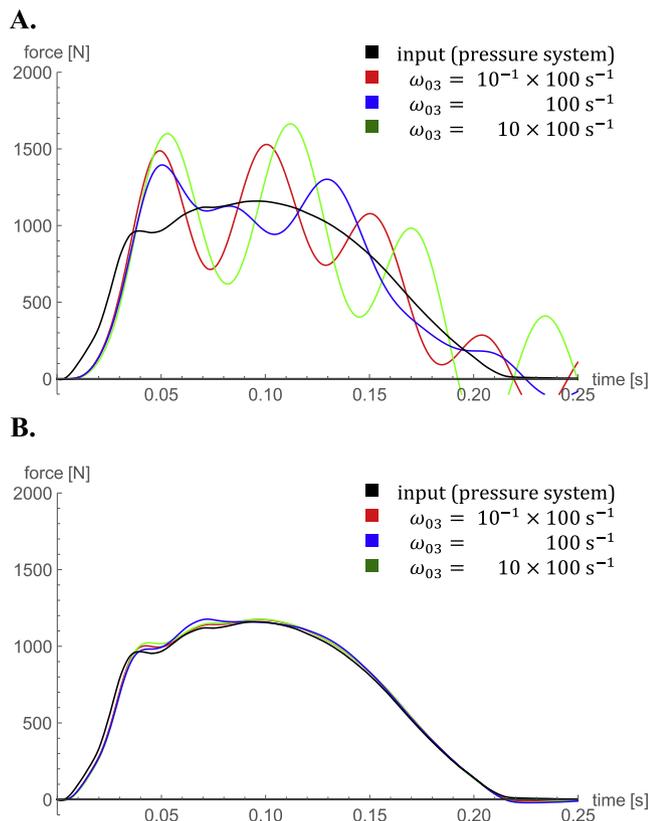


Fig. 3. A: Force measured by the force plate with a characteristic time $\tau_2 = 0.5$ for the treadmill (“Quinton model”) and variable natural angular frequency ω_{03} of the wobbling mass. The red line matches the force trace that was closest to the experimental data. B: Force measured by the force plate with a characteristic time $\tau_2 = 0.005$ for the treadmill (“Healthrider model”) and variable natural angular frequency ω_{03} of the wobbling mass. The red line matches the force trace that is closest to the experimental data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(1) increase in vertical force between measurement systems, (2) the oscillations in the force trace recorded on the force plates, (3) the differences in ground reaction forces across treadmills, and (4) how the forces recorded on an insole pressure measurement system remain the same despite differences in instrumented treadmill forces. Result 1 was primarily due to the wobbling mass and the inertial, damping and elastic forces of the treadmill such that the larger ground reaction force was “distributed” among the degrees of freedom of the system (three, in our simple model), resulting in a smaller force acting on the foot. Results 2 and 3, however, are likely explained by differences in the damping coefficients of the treadmill frame causing different oscillations and force magnitudes across treadmills.

Another interesting finding from this study was with respect to H2: the forces recorded on the force plate would be similar to insole pressure measurement system. Based on the data presented in Fig. 1, the insole pressure measurement produced similar measurements across the different treadmills. This result indicates that, depending on the treadmill set-up and characteristics, the forces recorded on an instrumented treadmill may not reflect the actual biomechanical forces acting on the runner.

6.1. Implications

The research community will benefit from these findings for three reasons (See [Supplementary Material 3 – Strengths and Limitations](#)). First, when using a force plate underneath a treadmill as seen in previous research (Belli et al., 2001; Dierick et al., 2004; Gosseye et al., 2010; Kram et al., 1998), considering the force plate reading as the ground reaction force actually acting on the person results in large errors, which then propagate to the computation of joint forces and moments during treadmill running. These, even small, differences in forces may propagate when calculating joint forces and moments and give rise to substantial errors (Collins et al., 2009). Second, we have provided a novel methodology to determine the differences in the ground reaction force acting on a person that are different than what was recorded on the force plate. Researchers can use our methodology to test their own instrumented treadmill set-up and consider if these force differences (magnitude and oscillations) are present in their instrumented treadmill set up (inexpensive or expensive). The model provided in this manuscript may help compensate for these oscillations before performing an inverse dynamics analysis during treadmill running rather than relying on a generic filter for these force oscillations (Kram et al., 1998; Kram and Powell, 1989). This statement is particularly true for the oscillations in the horizontal forces during level and inclined treadmill running ([Supplementary Fig. 1](#)). Last, instrumented treadmills are expensive and unobtainable for certain groups. If a research lab or clinic has a force plate, they could place the treadmill on the force plate, record the ground reaction force, and use our model to give an estimation of the ground reaction force truly acting on the runner.

6.2. Conclusion

Our results indicate that the ground reaction forces are different when running on a treadmill, but these differences are not as large as what is recorded from an insole pressure measurement system. Our model gives insight into an explanation for the oscillations that are present in an instrumented treadmill set-up and provides a method to correct for the force acting on a person during treadmill running. Our force-plate-treadmill-wobbling-mass model is a critical factor that researchers could consider when designing studies of treadmill gait.

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Author statement

All authors were involved in the study and preparation of this manuscript and this manuscript has not been submitted elsewhere.

Conflict of interest

No conflict of interest

Appendix A. Supplementary data

Supplementary Material 1: An experimental modal analysis was performed on the Healthrider and Quinton treadmills. The results of the experimental modal analysis show that the natural frequencies and damping characteristics of each treadmill were unique. The results of the experimental modal analysis are present in Supplementary Table 1.

Supplementary Material 2: In the main text, the force traces are presented for the vertical ground reaction forces. The oscillations in the instrumented treadmill data are also present in the horizontal ground reaction force. As a person runs on an incline, these oscillations become quite large in magnitude (Supplementary Figure 1A). Mostly researchers apply a filter to these data to smooth the force trace, but Supplementary Figure 1B exemplifies that these traces are difficult to filter without distorting the force trace. This distorted signal can largely influence the computation of joint moments with an inverse dynamics analysis. Our model could be implemented as a more effective filter for the force plate signal.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2018.12.025>.

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