International Journal of EXERCISE SCIENCE

Original Research

Evaluating the Effect of Shoes with Varying Mass on Vertical Ground Reaction Force Parameters in Short-Term Running

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ABSTRACT

International Journal of Exercise Science 15(1): 191-205, 2022. Past investigations have revealed that running shoes affect ground reaction force parameters. However, these studies are unclear as to whether these changes, which occur while running in different shoe types of differing masses, are the result of the structural design or the mass of the shoe. The main aim of this study is to evaluate the effect of shoe mass on vertical ground reaction force parameters: active peak and impulse. *Methods*. 21 male runners (24.52 years old (± 3.09) and 77.13kg (± 7.9)) participated in the experiment. A baseline shoe (BS) = 283g and four weighted shoes (shoe 2 = 333g, shoe 3 = 433g, shoe 4 = 533g and shoe 5 = 598g) were compared for 8 minutes of running on the instrumented treadmill. Each shoe was compared in a repeated measurement with the BS. Results showed that active peaks and impulses differed significantly ($p < .05$) between the BS and weighted shoes, except for shoe 2. From the threshold of 433g (shoe 3, which is 1.5 times heavier than the BS), we observed a significant increase in the vertical ground reaction force peak (1.86%) and impulse (1.84%). Other shoes such as shoe 4 and shoe 5, produced increasingly active peaks (N) of 2.08% N and 2.45% N compared to the BS. Increase of shoe masses in shoe 3, shoe 4, and shoe 5 resulted in an increase of impulse up to 1.84% Nm, 1.85% Nm and 2.49% Nm compared to the BS. Our determination of the shoe masses influencing these kinetic parameters may be a step towards reducing running-related injuries that result from accumulated microtrauma.

KEY WORDS: Running shoe; pair test; shoe mass; just noticeable difference

INTRODUCTION

The risk of injuries associated with running, particularly to the lower extremities, are often underestimated (10, 18, 30, 32, 53, 56). Such risks are related to a variety of intrinsic factors (4) including gender (41), foot type (8), and extrinsic factors such as running shoes (14, 52). Various types of running shoes have been developed to meet the needs of different types of runners, running styles, and running conditions (38). To further understand the effect of shoes on running biomechanics, researchers have compared different running shoes in the field of running economy (6, 43, 49) and kinematics (13, 15, 56). However, in the field of kinetics, few studies have investigated the effect of the mass of running shoes on active peak and impulse.

In running gait (in rearfoot or forefoot strikes), the curve of the vertical Ground Reaction Force (GRF) consists of two peaks: the passive peak is the result of the foot's initial contact with the ground, while the active peak results from the forces applied by the foot to the ground as it pushes off (16, 23). Active peak is one of the parameters of vertical GRF largely controlled by muscular activity (36). The magnitude and timing of active peaks may lead to musculoskeletal overuse injuries and osteoarthritis (47, 57). A parameter of active peak, namely peak of vertical GRF has been investigated in a few studies (17, 28, 29, 49, 50, 58). Kulmala et al. (28) determined that the maximalist shoe (320g) in comparison to traditional running shoe (304g) reveals a significant higher peak vertical GRF. In another study, Squadrone et al. (50) determined that Vibram four Fivefingers (148g) with traditional running shoes (341g) was determined by a greater peak vertical GRF. The findings of the aforementioned studies show that running shoes have an effect on peak vertical GRF but they are unclear as to whether these biomechanical changes are the result of the structural design or the mass of the shoe. Recently, a study by Wang et al. (54) investigated the effect of shoe mass alone on peak vertical GRF and evaluated the *minimum additional mass* which can significantly influence peak vertical ground reaction. However, their experimental design has certain limitations. Firstly, a blind test was not used. Several studies have determined that lighter shoes can improve performance (12, 45). Therefore, it is not surprising that lighter running shoes are more in demand for different levels of runners and shoe mass is ranked as one the most important characteristics of running shoes (19). Wang et al. (54) note that participants' expectations about the effect of shoe mass in running biomechanics (especially in running economy) may have generated biases in their performance (48) due to their open study as opposed to a blind test, exaggerating the effect size (21). They also did not include a measure of fatigue, such as Borg's rating of perceived exertion (RPE) scale (2), which influences peaks vertical GRF (33). However, Wang et al. (54) used preferred velocity in their experiment, stating that 'allowing participants to self-select the running pace facilitated a more natural response to running with additional mass on the shoes'. This approach is condoned by other researchers (7, 24, 39).

The effect of shoe mass on vertical GRF can be evaluated with respect to another variable, impulse, which has rarely been investigated. The impulses are measured to determine the total load on the body, composed of the force and its duration (4, 22, 34). Representing the time over which a force is applied allows evaluation of the pathomechanics associated with overuse injuries in the foot plantar (40). The purely mechanical system of running shoes becomes a biomechanical system once it interacts with the athlete (51). Therefore, a firm understanding of shoe characteristics such as shoe mass will help researchers to predict and/or determine running-related injuries which result from accumulated microtrauma (caused by an increase of vertical ground reaction forces (25)).

Somatosensory perception of shoe mass has been investigated in few studies in order to determine 'subjective threshold' by using the Just Noticeable Difference (JND) of various shoe masses through feet. This determination come from scaling of afferent signals from muscle, joint, and pressure receptors, or expectations of the relation between efferent and afferent signals (3, 9). JND is the minimum amount of shoe mass that must be changed in order to produce a noticeable variation in sensory experience. Slade et al. (48) observed JND of various shoe masses during optional movements, (jumping, walking, etc.). In their study, participants were asked how accurately they perceived the mass among weighted shoes through their feet (namely in a subjective measurement). The perceived mass or subjective threshold was measured subjectively using Visual Analogue Scale or binary questions. The perceived mass can also be ascertained by dividing the JND by the object's mass (intensity of a stimulus) (55), i.e., the 'Weber fraction' ratio. The question of whether changes in the shoe mass of the sensory threshold in such a subjective measurement can be observed by comparing vertical GRF parameters such as active peaks and impulses has been poorly understood.

Therefore, the first aim of this study is to evaluate the effect of shoe mass on vertical GRF with respect to the two variables: active peak and impulse. The second aim of this study is to investigate the minimum additional mass of running shoes which can influence peak vertical GRF and impulse, thus establishing an *objective threshold*, and to compare this with the subjective threshold of the somatosensory perception of additional shoe masses reported in the literature.

METHODS

This study included a pilot study in the form of an online survey, a one-day pretest and the main test on a separate day one week later. The online survey (the pilot study) was completed with 105 runners, most of whom were members of different running clubs in and around Munich (Germany), and some were also members of the Technical University of Munich sport center. Besides collecting biometric information, participants provided the following information:

Q. 1. Average velocity range (AVR) of all running sessions in the last 6 months
Q. 2. Average distance of all running sessions in the last 6 months
Q. 3. Average duration of all running sessions in the last 6 months
Q. 4. Average number of running sessions per week in the last 6 months

The goal of the pilot study is *to gain information from local runners to optimize the design of the experiment* and determine interest in participating in the main test.

Participants

Twenty-two male subjects (24.45 years old (± 3.20) and 77. 87 kg (± 8.6) participated in the day two experiment with one-week interval. Most of the participants in this study were who filled the online survey. Runners were required to be injury free six months before the time of testing. All participants gave written, informed consent prior to the experiment. The consent form assures confidentiality of participant data, presents the risks of the study, and protection of personal data through appropriate procedures for anonymization according to EU General Data Protection Regulation (42). In addition, the consent form assured participants they were free to withdraw from the research at any time without giving a reason and without penalty for not taking part. This research was carried out in accordance to the ethical standards of 1964 Helsinki Declaration (59) and IJES Ethics Statement (35)

Protocol
Indoor running shoes (Victory Performance, Deichmann GmbH, Germany) were chosen in a range of sizes from 42 to 45 and with an average weight of 283g. The weight deviation within shoe size was ± 3g and between the shoe sizes ± 21g. Each shoe size was categorized as one Baseline shoe (without additional mass) and shoes with four additional masses such as + 50g, + 150g, + 250g and + 315g (Table 1).

Table 1. Shoe mass number and total mass of a single shoe (*size 43*)

Shoe ID	Total mass	Ratio
BS*	270g (± 3g)**	1
shoe 2	320g	1.18 × BS
shoe 3	420g	1.55 × BS
shoe 4	520g	1.92 × BS
shoe 5	585g	2.16 × BS

*Baseline shoe = BS. ** Mass tolerances within the shoe size

1.a **1.b** **1.c**

Figure 1. Preparation of experimental shoes. 1.a Indoor running shoe (Baseline) 1.b Lead tape added to fore and rear parts 1.c Concealed with the black tape

Increasing different levels of shoe mass partly follows Slade et al. (48), who, in an earlier study, used different shoe masses in somatosensory perception. However, to increase the shoe mass, one main criteria, i.e., the durability of the material used to increase the shoe mass while running at various velocities, was tested in parallel to this study. In comparison to other materials (e.g. plasticine), we determined that lead tape was more durable up to an additional mass of 330g (in upper velocity of 16km/h), after which it was too heavy to remain fixed. To ensure the stability of the additional mass, we set the upper limit at 315g.

The Gaitway-3D 150/50 treadmill from H/P Cosmos® (Germany) with a conveyor belt 1500 mm (long)× 500 mm (wide) was used. Its speed range can be varied between 0 to 22 km/h. This treadmill was equipped with four strain gauge transducers from Arsalis® (1). The sensors are defined with linearity and hysteresis defined $F_z < 0.2\%$ and F_y and $F_x < 0.8\%$ and a sample rate of 1000Hz. The heel-strike impacts during running generated vibrations on the treadmill, which could not be completely prevented. The disturbances in the measurement data due to these vibrations were largely eliminated by a Butterworth low-pass filter of 10^{th} order and 18 Hz.

The tool for measuring participants' effort and exertion was the Borg's RPE scale (6-20). Participants were asked to rate their exertion during the activity, taking into consideration feelings of physical stress and fatigue, while disregarding factors such as leg pain or breathlessness but focusing on the whole feeling of exertion.

The purpose of the day one (pre-test) was to familiarize participants with the concept of perceived exertion (Borg's RPE, 6-20), acquaint them with the treadmill run, and establish their preferred velocity for the day two (main) test. In total, the participants had ten minutes to warm up according to the following protocol: In the first five minutes, they ran five minutes on the treadmill at their desired velocity (with the BS). They then performed six movements: quad piriform walk, hip opener, arm circles, Frankenstein walk, leg crossover and inchworm (following the experimenter's instructions).

To start the experiment, it was necessary to find the *preferred velocity* for each participant for day one that would also be used on day two. Participants defined their preferred velocity for the experiment under blind test conditions aided by the experimenter. To determine the preferred velocity for each participant, we took an average range velocity (ARV) from across the sample population of participants (n = 105) in the online survey (Q.1). This was 10–12 km/h. The experimenter then set the treadmill to a velocity within the ARV. The participants requested reduction or increase in velocity until their_preferred velocity was reached. In a first session, participants ran with the BS for 2 minutes before putting on another pair of weighted shoes and running for 2 minutes. They repeated this step for all weighted shoes and the BS. Participants were asked to complete RPE scale (6-20*)*, thirty seconds before accomplishing the running with BS and weighted shoes.

Shoe order was randomized among participants to avoid learning effect. After completing all possible pair tests with the BS, subjects were given up to-one hour until they felt ready to start the second session, following the same procedure as in the first session. After the second session, participants could choose whether to continue with the main test or not.

In the day two (main test), one participant dropped out for reasons undisclosed. In total, 21 male runners (24.52 years old (± 3.09) and 77.13kg (± 7.9)) attended the main experiment voluntarily. All wore identical socks – Falke KGaA – (45% Polypropylene, 35% cotton, 20% Polyamide) to minimize sensation variation. After warming up for 10 minutes (as on day one, pretest) participants ran on the treadmill with the BS for 2 minutes. Immediately after this, the participants changed to one of the weighted pairs of shoes and then ran for 8 minutes. Afterwards, they put on the BS and ran for 2 minutes before putting on another pair of weighted shoes and running for 8 minutes. They repeated this step for all weighted shoes and the BS (see Table 2). Participants took 100 seconds rest after tests 2, 4, 6 and 8 (Table 2). During the 8 minutes run with all weighted shoes and the BS (tests 2, 4 ,6, 8 and 10), the data on ground reaction forces were collected for 30 seconds at each of the following intervals: first phase from 1´30´´, middle phase from 4´30´´, and final phase from 7´30´´. The Borg'a RPE scale was completed five times in Tests 2, 4, 6, 8 and 10 (Table 2) and at the following intervals (including the warm up duration): 20´30´´, 33´10´´, 45´50´´, 58´30´´ and 71´10´´ (in the final phase). The whole experiment including warm up and rest duration lasting 73´20´´.

Table 2. Running with different shoe masses at day-two test (example with random order for weighted shoes)

#Test	ID	Running Duration	TNCS**	#Test *	ID	Running duration	Rest
1	BS	2min	60 seconds	*2*	shoe 2	8min	100 seconds
3	BS	2min	60 seconds	4	shoe 4	8min	100 seconds
5	BS	2min	60 seconds	*6*	shoe 3	8min	100 seconds
7	BS	2min	60 seconds	8	shoe 1	8min	100 seconds
9	BS	2min	60 seconds	*10*	BS	8min	-

On day two (main test) and during each 8 minutes run, the peak of vertical GRFs was measured for three phases (phase one from 1´30´´, phase two from 4´30´´, and phase three from 7´30´´) for a duration of 30 seconds. The vibrations of the treadmill while impact running could not be completely prevented. Hence, a custom software written in Visual Basic 6.0 converted the output from each force sensor to net vertical GRF. Data collected at 1000 Hz were smoothed with a fourth-order low pass Butterworth filter at a cutoff frequency of 18 Hz. The averages of all peaks for BS and weighted shoes in each phase were then calculated.

Impulse was measured for each shoe mass for each three phases. Vertical forces of stance phases were measured for 30 seconds with respect to the weighted shoes and BS. The integral of force-time was calculated for each stance phase. Finally, the average integral of the stance phases for a certain shoe mass was calculated.

Regarding pre-test and test conditions, the room temperature was constant (23-25°C) for both days one and two. In addition, participants were asked to comply with the following instructions before both pre-test and main test:

1. Avoid heavy training the day before the tests.
2. Abstain from alcoholic beverages the day before both tests.
3. Ensure a minimum of 6 hours sleep the day before both tests.
4. Do not consume a heavy meal 3 hours before either test.

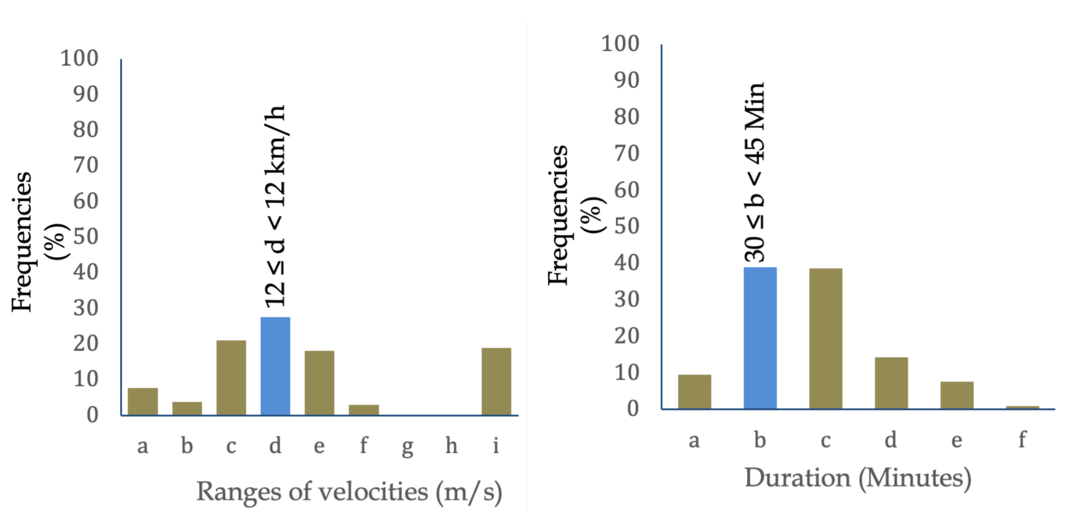
There was a week interval between the tests, which both began at the same time of day. Participants were asked not to touch or handle the shoes at any stage during the test of mass perception through the feet. The experimenters put the shoes on subjects' feet, laced them and removed immediately them after the test. Participants were not allowed to walk or jump in the shoes. They began running on the treadmill immediately after lacing. These procedures prevented the participants gaining any perceptual information about shoe mass that could confound their perception.

Statistical Analysis

Data on peaks vertical GRF and impulses (force-time integral) were collected and measured from all participants with different shoe masses for 30 seconds at the three-time phases. Then, we determined 'objective threshold', the minimum additional mass of running shoes which can significantly influence peak vertical GRF and impulse. Repeated measures ANOVA with Bonferoni correction (significance level of 0.05) was used to compare different shoes masses with the BS in statistical software SPSS. Data on perceived exertion was collected five times for each participant . Data of perceived exertion was collected for all participants in five times in Tests 2, 4, 6, 8 and 10 (in the final phase). A Spearman's rank-order was used to determine whether there is correlation between time (five-time phases) and RPE.

RESULTS

The results of the online survey (Figure 2) showed 'Average velocity of all running sessions in the last 6 months' chosen by highest frequency of 27.6% ranged between 10-12 km/h (Figure 2.a). In the second question, 'Average duration of all running sessions in the last 6 months', 40% of participants reported an average duration of 30-45 minutes, and 39.5% reported 45-60 minutes (Figure 2.b)



2.a Average range velocity of all running sessions in the last 6 months (Q.1)

2.b Average duration of all running sessions in the last 6 months (Q.2)

Figure 2. Results of two questions of the survey (n = 105)

In the third question (Q.3), 31% of participants answered 'Average distance of all running sessions in the last 6 months' with a rate of 5-7 km as majority and 26.5% answered with a rate of 7-9Km. And finally, most participants (49.5%) chose one running session per week (Q. 4).

Active peak and Impulse: The peaks of vertical GRFs for weighted shoes and the BS were measured in three phases. To measure the effects of time and shoe mass and their interaction, an ANOVA with repeated measures was used. The results indicated that the assumption of sphericity was not violated for the Peak of VGRFs and Impulses. Thus, Mauchly's Test of Sphericity was performed (Table 3 and 4).

In particular, there was a significant effect of only shoe mass *on peak vertical GRF*. Wilks' Lambda = 0.001, F (4.17) = 8.421. Only shoe mass had a significant effect *on impulses*. Wilks' Lambda = 0.000018, F (4.17) = 15.23. There was no interaction effect of these two independent variables on both dependent variables. In addition, shoe mass independent variable showed a large effect size on both dependent variables VGRF and Impulse respectively 0.66 and 0.78. Time, another independent variable shows small effect size (26) on both dependent variables VGRF and Impulse respectively 0.002 and 0.02.

Table 3. Multivariate Test of peak of GRFs-main and interaction effects

	AM[1]	Value	*F*	Sig.	PES[3]	HPd[4]	Error *df*
Time	WL[2]	0.99	0.01	0.98	0.002	2	19
Mass	WL	0.33	8.42	0.001	0.66	4	17
Time × Mass	WL	0.73	0.59	0.76	0.26	8	13

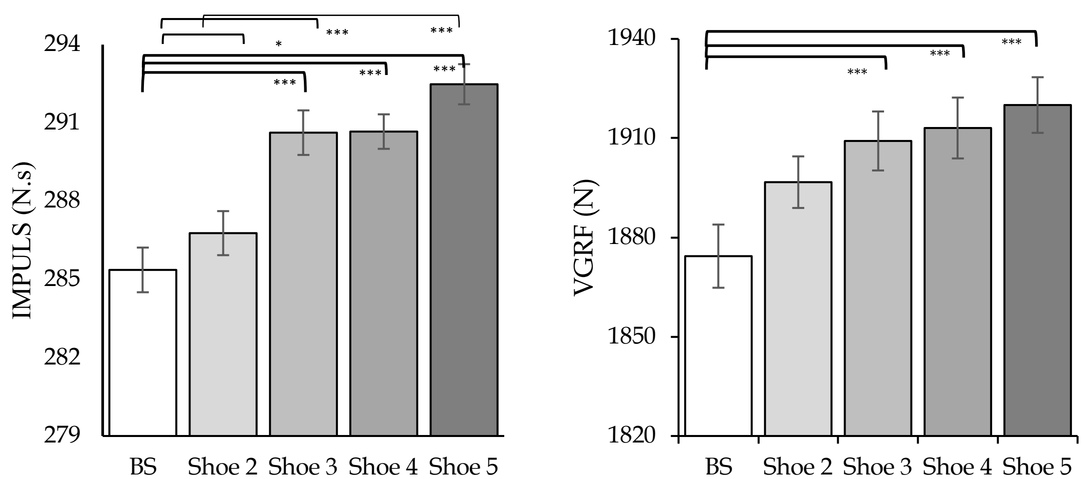
[1] Adjusting Method, [2]WL = Wilks-Lambda. [3] PES = Partial Eta-Squar. [4] Hypothesis df

Table 4. Multivariate Test of Impulse- main and interaction effects

	AM[1]	Value	*F*	Sig.	PES[3]	HPd[4]	Error *df*
Time	WL[2]	0.97	0.26	0.77	0.02	2	19
Mass	WL	0.21	15.23	0.000018	0.78	4	17
Time × Mass	WL	0.61	1.009	0.47	0.38	8	13

[1] Adjusting Method, [2]WL = Wilks-Lambda. [3] PES = Partial Eta-Squar. [4] Hypothesis df

To compare group means, post hoc comparisons using Bonferroni correction were performed. As shown in Figure 3, the results indicate that peak vertical GRF and the impulses of running shoes with additional mass, 150g, 250g and 315g, differed significantly from those of the BS.



a. Impulse

b. Peak vertical GRF

Figure 3. Mean comparison (and standard errors) of impulses (a) and peaks vertical GRF(b). When $P \leq 0.001$ and $P \leq 0.05$ are respectively indicated with *** and *.

In addition, the impulses of the running shoe with 50g additional mass differed significantly from those with additional masses of 150g, 250g and 315g.

Borg's Rated Perceived Exertion: The average RPE was 12.96 (SD = 1.29) and the frequency of RPE was highest between 13 and 14 (see Figure 4). A Spearman's rank-order correlation was used to determine whether rated perceived exertion was influenced by the duration of the experiment. The null hypothesis is defined as time having no effect on RPE during the experiment. The result shows there is no statistically significant correlation (p = .196) between RPE and time (five-time phases).

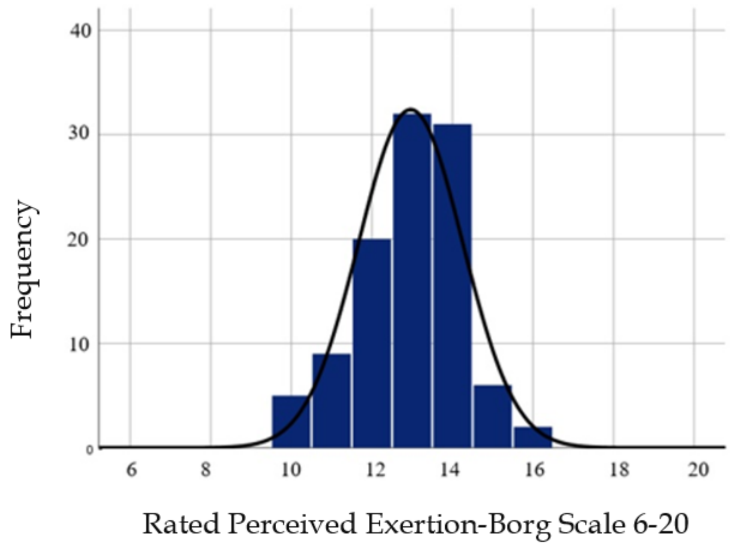


Figure 4. Histogram of rated perceived exertion RPE (n = 21 participants × 5 shoes = 105)

DISCUSSION

The first aim of our study was to evaluate the effect of shoe mass on peak vertical GRF and impulse, among identical shoe structures. Our findings determined that when additional masses reach to + 150g (total shoe mass = 333g), + 250g (total shoe mass = 433g) and + 315 (total shoe mass = 598g), there were significant increases in both variables, peaks vertical GRF and impulses. In particular, our findings show that the peak of vertical GRF significantly increases with a minimum additional mass of + 150g (between the BS (283g) and shoe 3 (433g)).

These findings are in line with those of Wang et al. (54), who showed an increase of shoe mass from 255g to 415g, with a minimum additional mass of 160g, which results in a significant increase of peak of vertical GRF. However, there is disconformity in the amount of the increase of peak vertical GRF when the minimum additional mass is. In our study, there is an increase of 1.86% of peak vertical GRF, while in Wang et al. (54), this reaches 3.5%. This difference could be linked to the methodological difference. In their study (54), a force plate has been used, however force plate method may limit the length of the run and makes it difficult to simulate natural running at a constant velocity in a laboratory situation (44). In addition, an instrumented treadmill has been shown to be a highly valid tool for the assessment of vertical GRF, especially for active peak (27). It also allows measurement of peak vertical GRF at the 'preferred velocity' over a longer period (39). Furthermore, in our study, a number of factors were controlled for in order to control biases in the experiment. We used a blind test condition and included BS running period between other running periods with the weighted shoes (see Table 2).

Findings of another study, Kulmala et al. (28) determined that the Maximalist shoe (321g) showed an increase of 2.8% at the peak of vertical GRF in comparison to the Baseline shoe (304g). Although their study was able to show a difference between two shoes, as these shoes were not identical, the different shoe design (e.g. midsole thickness) may thus have played a role in registering difference in vertical GRF.

In our study, the preferred velocity follows the methodology in studies (7, 24, 39, 54), where it was concluded that 'asking the subjects to run at the same velocity may have altered their preferred normal running style'. However, to reach to such a preferred velocity, we *did not* simply start from a lower limit e.g. 6 km/h and increase the velocity until the preferred velocity was reached, nor did we decrease from an upper limit e.g. 16 km/h. To avoid bias, we started with an online survey tool (Q.1) and pre-test to reach to the preferred velocity (explained above in the Methodology section). It is important to emphasize that we used their preferred velocity on the treadmill, which can be different from their velocity on terra firma during their own exercises (5). In addition, another two questions (Q.2 and Q.3) in the survey helped us to establish the average range, duration and distance run and therefore to set up the experimental design. And finally, based on the information from the fourth question (Q.4) in the survey, we were able to complete the experiments (pre-test and main test) in two days on consecutive weeks.

In our research, the effect of heavier shoes (shoe 3, shoe 4 and shoe 5) on peak vertical GRF and impulses can be interpreted by employing Nigg's paradigm theory (37). He determined that 'changing into different shoes usually fails to produce major changes (despite a few minimal changes) in joint kinematics because the neuromuscular system prefers a specific, individual kinematic pattern, called the preferred movement path'. Based on this paradigm, we speculate that when shoe mass interferes with this "path", the neuromuscular system counteracts with muscle activation, such that the original movement pattern is preserved. However, fatigue might have a distorting influence on Nigg's paradigm. In our study, the perceived exertion, which correlates to the measurement of fatigue (11), was measured using Borg's RPE scale. According to the Spearman rank order, there is no statistically significant correlation between RPE and the five tests order. This leads us to accept the null hypothesis where there was no discernable time effect on RPE during our experiment. In addition, the average rate of perceived exertion of the Borg's RPE Scale (6-20) is 12.86 (SD = 1.29), where the maximum frequencies occur at rate 13 and 14 in the middle of the Borg's RPE scale. Thus, we can conclude that the effect of fatigue was not significant.

Besides additional shoe mass, + 150g, other shoes such as shoe 4 and shoe 5, produce increasingly active peaks (N) of 2.08% N and 2.45% N compared to the BS. The effect of shoe mass on vertical GRF was also measured with impulse. An increase of shoe mass in shoe 3, shoe 4, and shoe 5 resulted in an increase of 1.84% Nm, 1.85% Nm and 2.49% Nm compared to the BS. Measuring the cumulative force over the stance phase is a sensitive variable, which also illustrates the difference between shoe 2 (additional 50g mass) and the other weighted shoes.

Since the magnitude of active peaks is positively correlated with tibial peak force (31), the increase of active peaks and impulses in our study can increase the risk of overuse injuries e.g., tibial fracture injuries (15). On the other hand, the biological tissue adapts to the level of stress placed upon it, and this adaptation may lead to positive remodeling if the applied stresses are below the tensile limit (20). Future study should investigate whether the minimum shoe mass difference observed in our study (+ 150g) can remodel biological tissue positively in longitudinal studies over short and long periods of running time.

The second aim of our study was to 'investigate the minimum additional mass of running shoes which can significantly influence peak vertical GRF and impulse, thus establishing an *objective threshold*, and to compare this with the subjective threshold of the somatosensory perception of additional shoe masses reported in the literature'. Our findings determined that the minimum additional mass producing a significant difference in the active peak and impulse is 150g. The difference in the objective measurement was determined by a Weber fraction ratio of 0.53 (150g: 283g). On the other hand, the Weber fraction in the study of Slade et al. (48) was calculated by dividing just noticeable differences of mass (142g) by the original mass of the shoe (220g), which is equal to 0.64 (142g: 220g). Comparing the results of our study with the subjective measurements such as those found by Slade et al. (48) shows that these ratios are close. However, the change may be caused by the methodological difference in the original shoe masses of both studies, which is around 63g. This difference may affect the subjective threshold, where the Weber fraction decreases when the mass increases up to 200g (46).

In our study an increase of shoe mass up to 150g (BS = 283g) did not show a significant effect on peak vertical GRF and impulse. However, in a subjective study by Slade et al. (48), the perception of mass up to an additional mass of ~140 g (BS = 220g) could not be observed by runners. Thus, it can be cautiously recommended that shoe developers e.g. trail running shoe designers, can therefore design a shoe by adding up to + 140g mass and a Weber fraction of 0.64, to enhance other shoe characteristics such as stability and traction. However, future studies should investigate the effects of long-term running, where exposure to fatigue, energy consumption and kinetic changes play a greater role.

Conclusion: The findings of this study show that peaks of GRF and impulses differed significantly between the baseline shoe and weighted shoes with different shoe masses 150g, 250g and 315g but not 50g. The additional shoe mass of 150g (1.55 ×BS) was shown to be the mass intensity threshold between other masses when compared to the BS. Determining minimum shoe mass, which can influence the kinetic parameters, may be a step towards reducing running-related injuries (resulting from accumulated microtrauma) and also understanding the perceived force and perceived heaviness during running. Future studies should investigate the effects of long-term running, where exposure to fatigue, energy consumption and kinetic changes play a greater role.

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Appendix

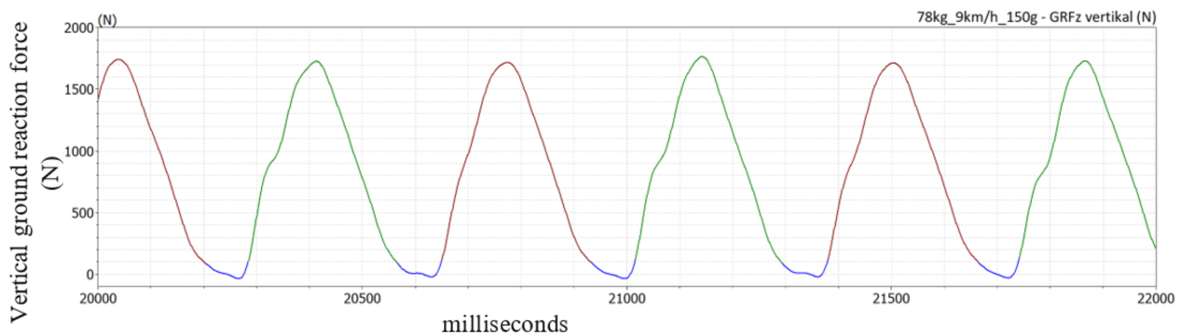

Figure 5. A 2-second cutout from a 30-second typical measurement curve from the study. Standing phases of the left leg in red, the right leg in green (a custom software written in Visual Basic 6.0)

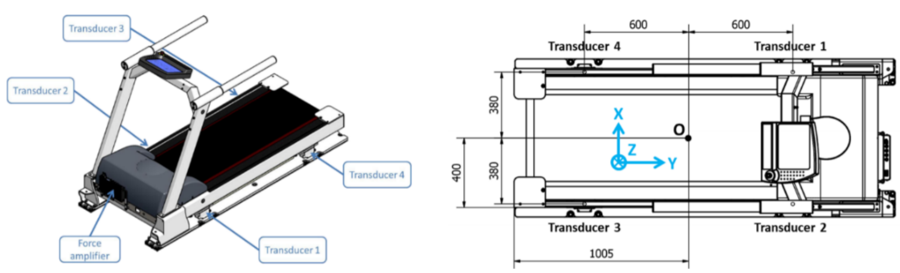

Figure 6. Schematic of Gaitway-3D from H/PCosmos