



Article

Effects of Jogging with a Hydration Pack on Ground Reaction Forces

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Abstract

Background/Objectives: Long-distance running often requires athletes to carry their own hydration. Both the velocity of the runner and the load will affect the ground reaction forces (GRFs). Furthermore, carrying a liquid mass may have different outcomes on GRF compared to carrying a solid mass. This effect may in turn potentially result in a greater risk of injury. The goal of this study was to examine the GRF while jogging with different quantities of water in a hydration pack. It was expected that GRF measures would change with increased hydration pack weight. **Methods:** Twenty college-aged participants were asked to run over a force plate with an empty hydration pack and packs (0.71 kg) filled with 0.5 litres (1.21 kg), 1.5 litres (1.71 kg), and 2.5 litres (3.21 kg) of water. **Results:** No significant differences ($p > 0.05$) in the vertical, lateral, or forward–back measures were found between the different loads. These outcomes may be a result of the dampening effect the movement of the water may have on gait. **Conclusions:** It is believed that the benefit of having hydration readily available via a hydration pack will outweigh any potential for injury due to the added weight being carried.

Keywords: gait; running; backpack; injury; kinetics



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1. Introduction

Running is one of the purest sports, as it requires minimal equipment and no facilities. In North America, 17.6 million runners registered for an organized race in 2020 [1]. Many of these individuals seek to challenge themselves by running in longer distance races. Marathons (42.2 km) and ultramarathons (>42.2 km) have seen an exponential rise in registered racers. In 2018, nearly 1.3 million runners completed the marathon distance, a 49% increase from 2008, and there were 611,098 worldwide ultra-running participants in 2018, a 1675% increase since 1996 [2]. With such an increase in participation, the need to study injury-related mechanics is of the utmost importance.

Running a marathon requires an individual to take approximately 30,000 to 50,000 steps. With these many steps, the repeated impact experienced by the body can potentially result in chronic injuries. The magnitude and nature of the ground reaction forces depend on several factors. The primary factors include the individual's body weight, pace and efficiency [3]. However, the mechanical makeup of the shoe [4] and surface also has an influence [5]. All these factors influence the vertical ground reaction forces placed on the body while running.

The vertical ground reaction forces (vGRFs) have been found to be linearly related to pace. At $1.5 \text{ m}\cdot\text{s}^{-1}$ an individual experiences vGRF that are approximately 1.2 times their body weight (BW) and increase to between 2.0 and 2.5 BW at $4.5 \text{ m}\cdot\text{s}^{-1}$, which equates to a 6-min per mile pace [6,7]. In addition, the loading rates during foot landing range from 8 BWs^{-1} at $1.5 \text{ m}\cdot\text{s}^{-1}$ to 113 BWs^{-1} at $5.0 \text{ m}\cdot\text{s}^{-1}$ [7,8]. The repeated impact forces are associated with overuse injuries of the musculoskeletal system [9], and with a growing number of participants in the marathon and longer distances, injury prevention is paramount.

When running longer distances, individuals require greater amounts of hydration and nutrition. In some cases, aid stations provide these supplements throughout the racecourse. However, at the marathon distance many still choose to carry their own supplements. At greater distances, the need to carry their own supplements increases. The added weight of packs filled with hydration and/or nutritional supplementation increases the impact loads during running. Surprisingly, little is known about the effects of the additional weights on running kinetics. At present there are no known studies examining the effects of hydration packs on ground reaction forces while jogging.

The effects of a pack on gait have been studied among the military and recreational hikers. Significant proportional increases of 8 kg loads in both the vertical and anteroposterior GRF while walking at $1.5 \text{ m}\cdot\text{s}^{-1}$ in military were found [10]. Similar changes in recreational hikers at a similar pace were found, where loads of 20% and 30% proportionally increased vertical and anteroposterior ground reaction forces as well as stance times [11]. Increases in vertical GRF are linked to overuse injuries [12] and changes in the anteroposterior GRF results in greater braking, reducing running economy [8].

Separately, both pace and external loads alter the GRFs. However, there are no known studies examining the GRFs during jogging with a hydration pack (containing liquid) that is not as heavy as those typically used by military or recreational hikers. A liquid mass has different dynamics than a solid mass. This knowledge could provide preliminary data as to the nature of the influence of hydration packs on joggers, and whether potential chronic injuries are enhanced by wearing a pack. The purpose of this study is to examine the ground reaction forces while jogging with a rear-mounted hydration pack. It was hypothesized that there will be increases in ground reaction forces with increases in hydration pack weight via fluid levels; however, the degree of increase and in which components are not certain.

2. Materials and Methods

2.1. Participants

G*Power [13] was used to determine the appropriate number of participants, using a medium effect size (Cohen's f) of 0.25 [14], alpha of 0.05, power set at 0.90 with four groups and eight measures using repeated measures analysis of variance, within factors analysis. The correlation among repeated measures was set to 0.5 and the non-sphericity correction was set to 1. Therefore, 20 participants were recruited from the local community. Participants were healthy individuals who exercised consistently and used running as one of their regimens. Ten female and ten male individuals volunteered for the study (Mean $\pm$ standard deviation age 26.7 ± 2.6 years; height = 171.5 ± 13.5 cm; weight = 75.1 ± 17.1 kg). To ensure participants were healthy and devoid of injury that would preclude safe exercise, a Physical Activity Readiness Questionnaire was completed (PAR-Q+). In addition, a written consent form approved by the institution's ethics review board was signed.

2.2. Procedures

Participants were asked to wear their own running shoes to ensure no alterations in gait patterns were due to wearing unfamiliar shoes. A four-minute treadmill warm-up was

provided prior to data collection. Participants started with a speed of 4.8 km/h (3.0 mph) and a zero-percent gradient. After every 15 s the speed was increased by 0.16 km/h (0.1 mph) for the duration of the warm-up.

Following the warm-up, participants put on a hydration pack (Osprey Duro 15, Cortez, CO, USA; Figure 1) and straps were adjusted to their personal preference. Reflective markers (approximately 1 cm in diameter) were placed directly over the left and right anterior superior iliac spine. To ensure familiarization of the pack and a natural foot placement on the two force plates, participants were given unlimited practice runs. They were instructed to run as naturally as possible, without looking down and to run at a moderate pace. The force plates were embedded two-thirds down a runway that was approximately 30 metres long. This gave sufficient distance before and after the force plates to ensure a natural gait pattern.



Figure 1. Image of the hydration pack and bladder. Four separate bladders were used in this study such that the pack remained on the participant for all trials.

Two sets of trials were performed using four different hydration bladders, each filled with different amounts of water: empty pack (0.71 kg), 0.5 L (1.21 kg), 1.5 L (1.71 kg) and 2.5 L (3.21 kg). The pack stayed on the participant and only the bladders were changed, to ensure consistency in the pack between all trials. The water remained sealed inside the bladders until all testing was completed.

A successful trial was defined as one where a single foot landed subsequently on each force plate and the gait pattern was maintained (i.e., no shuffling before foot strike on the force plates). The order of trials was randomized between participants, though both trials per water amount were performed together. Eight total successful trials were recorded per participant and used for data reduction (Figure 2).

Ground reaction force data were collected at 1000 Hz from two Bertec (Columbus, OH, USA) force plates (model 6090-15) and captured using OptiTrack Motive (version 2.3.0) motion capture system software. All force plate data were smoothed using a fourth-order Butterworth low-pass filter set to 10 Hz.

Velocity was measured by averaging the velocity derived from the left and right anterior superior iliac spine markers, just prior to the participant's right foot landing on the first force plate to just after their left foot was off the second force plate. Force plate data from the right and left foot were combined for each of the trials and was used for analysis. Seven dependent variables were determined from the GRF data and included impact peak, vertical loading rate, maximum vertical force, maximum braking force, maximum propulsive force, peak media, and peak lateral. Loading rates were calculated using the time between the vertical ground reaction force at 50N and body weight plus 50 N [8]. The vertical GRF data were normalized to the participant's body weight including the different pack weights.

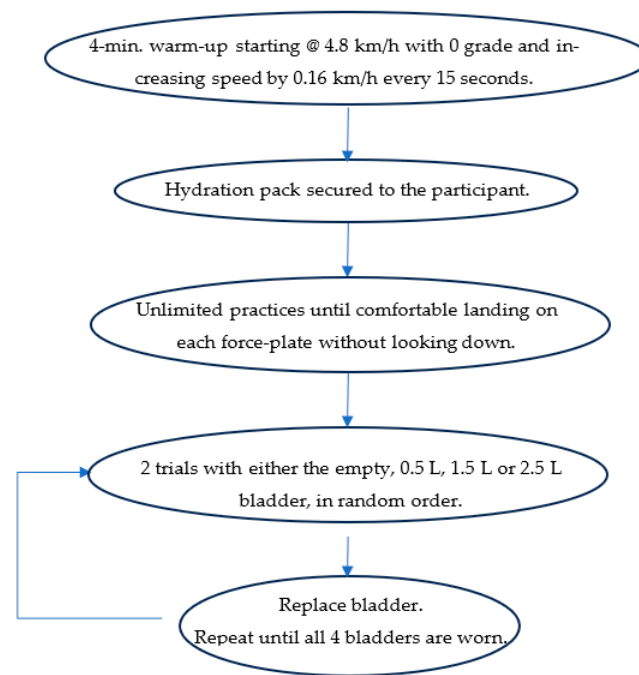


Figure 2. Schematic diagram of the testing session for a single participant.

2.3. Statistical Analysis

Once all data was collected, descriptive statistics were calculated and included the mean and standard deviations for the five dependent variables. An initial repeated (within-sample) measures analysis of variance was conducted ($\alpha = 0.05$) to determine whether there was a significant difference between the average velocities across the four conditions (amount of water in the hydration pack). This initial test was used to determine whether velocity would need to be factored out of the analysis of the variance between the five dependent variables (impact peak, maximum braking force, maximum propulsive force, peak medial-lateral forces and loading rates) across the four conditions.

The primary analysis included five separate repeated (within-sample) measures of analysis of variance conducted on the five dependent variables across the four conditions (independent variable). Greenhouse-Geisser was used to account for any violations of sphericity. Post hoc analysis for significant main effects was conducted using the Bonferroni test. A Bonferroni adjustment was made due to performing five analyses on the same data set. Therefore, α was set at 0.01 to adjust for the five tests. Effect size was calculated using partial Eta squared to determine the amount of variance in the five dependent variables that were accounted for by the different weights in the hydration pack (i.e., the conditions).

3. Results

3.1. Average Velocity

The average velocities across the force plates were very similar between the four conditions (Table 1). There was a slight decline in the average velocity as the weight of the pack increased, though not significant ($F(3,57) = 0.97$, $p = 0.38$). The average velocity with the empty pack ($2.90 \pm 0.45 \text{ m}\cdot\text{s}^{-1}$) was only $0.12 \text{ m}\cdot\text{s}^{-1}$ faster than with the full 2.5 L pack ($2.78 \pm 0.36 \text{ m}\cdot\text{s}^{-1}$). Eta-squared showed a negligible effect (>0.01) [14] of the pack on average running velocity ($\eta^2 = 0.08$).

Table 1. Means $\pm$ standard deviations of the biomechanical measures across the four conditions. No significant differences ($p > 0.01$) were found. VLR = vertical loading rate. Peak impact, VLR and maximum vertical force were normalized to body weight (BW). Bold numbers are best average, and underlined numbers are worst average for each measure.

	Empty	0.5 L	1.5 L	2.5 L
Velocity ($\text{m}\cdot\text{s}^{-1}$)	2.90 $\pm$ 0.45	2.85 $\pm$ 0.39	2.83 $\pm$ 0.37	<u>2.78 $\pm$ 0.36</u>
Peak Impact (BW)	1.44 $\pm$ 0.46	1.48 $\pm$ 0.38	1.44 $\pm$ 0.35	<u>1.47 $\pm$ 0.36</u>
VLR ($\text{BW}\cdot\text{s}^{-1}$)	48.88 $\pm$ 18.74	<u>54.79 $\pm$ 19.33</u>	50.96 $\pm$ 19.60	52.32 $\pm$ 21.11
Max Vertical (BW)	2.23 $\pm$ 0.23	<u>2.30 $\pm$ 0.13</u>	2.24 $\pm$ 0.14	2.26 $\pm$ 0.12
Max Brake (N)	<u>259.44 $\pm$ 83.38</u>	257.25 $\pm$ 81.53	250.44 $\pm$ 71.62	259.14 $\pm$ 74.53
Max Propulsive (N)	168.96 $\pm$ 44.03	172.04 $\pm$ 45.41	<u>178.93 $\pm$ 47.83</u>	177.44 $\pm$ 47.94
Max Medial (N)	68.52 $\pm$ 37.85	67.40 $\pm$ 49.93	<u>69.59 $\pm$ 31.40</u>	69.19 $\pm$ 38.21
Max Lateral (N)	81.86 $\pm$ 43.59	<u>83.08 $\pm$ 45.10</u>	71.74 $\pm$ 37.95	78.19 $\pm$ 41.16

3.2. Peak Impact and Vertical Loading Rate

The two vertical measures during the landing phase (peak impact and vertical loading rate), were statistically not significant across the conditions ($F(F(3,57) = 0.35, p = 0.73$; $F(3,57) = 1.75, p = 0.20$, respectively). There was very little variation in either of these measures. The average peak impact was highest with the 0.5 L pack (1.48 ± 0.38 BW) and lowest was seen in the empty and 1.5 L trials (1.44 ± 0.46 and 1.44 ± 0.35 BW, respectively). Similarly, average vertical loading rates were highest in the 0.5L condition ($54.79 \pm 19.33 \text{ BW}\cdot\text{s}^{-1}$) and lowest with the empty pack ($48.88 \pm 18.74 \text{ BW}\cdot\text{s}^{-1}$). Eta square measures indicated that negligible-to-small effects (0.01 to 0.2) [14] on peak impact and vertical loading rate were attributed to the amount of water in the pack ($\eta^2 = 0.02$ and 0.12, respectively).

3.3. Maximum Anteroposterior and Mediolateral Force

Maximum anteroposterior (braking and propulsive) and mediolateral forces had no statistical differences across the conditions ($F(3,57) = 0.52, p = 0.64$ and $F(3,57) = 1.06, p = 0.36$, respectively, for braking and propulsive; $F(3,57) = 0.05, p = 0.95$ and $F(3,57) = 1.33, p = 0.28$, respectively, for medial and lateral). There was a slight (approximately 10 N) increase in the maximum propulsive forces as the weight of the pack increased. In addition, the maximum lateral forces for the empty and 0.5 L trials were approximately 10 N higher than the averages for the 1.5 and 2.5 L trials. For all four measures, the effect sizes ranged from negligible to negligible-to-small [14], ranging from $\eta^2 = 0.003$ to 0.070.

4. Discussion

This study examined the ground reaction forces (GRF) during jogging with a hydration pack filled with different amounts of water, ranging from empty to full (2.5 L). Overall, there was no effect of different loads of hydration packs on any of the GRF measures. Furthermore, negligible variation in GRF was attributed to the differences in the weight of the hydration packs as seen in the calculated effect sizes. Two primary factors within this study directly related to the relative GRF during gait are the speed the participants' run, and load carried. The speed was kept at a constant to represent longer-distance paces where hydration packs are typically used. The approximate speed of the participants in this study was $2.8 \text{ m}\cdot\text{s}^{-1}$ equating to a 4-h and 12-min marathon pace. This pace is similar to the median finishing times in the Boston, New York City and Chicago marathons of 4 h and 8 min [15] for the age group specific to the participants in this study.

The maximum vertical forces and vertical loading rates in this study were similar to those found in previous studies [7,16,17]. Increased loads through increased amounts of water in this study did not have a significant effect on the vertical kinetic measures.

Birrell et al. [10] found loads added in 8 kg increments had significant effects on ground reaction force measures among military personnel walking at $1.5 \text{ m}\cdot\text{s}^{-1}$, equating to approximately half the speed but double the weight of this study. This discrepancy may be due to significantly larger vertical impulses during walking compared to running at comparable speeds [16]. This difference between the two gait patterns is partially attributed to differences in motor programmes and mechanical outcomes between those gait patterns. Furthermore, the effect of total mass normalization on GRF parameters may depend on interactions between spatiotemporal parameters and kinematics [18].

During the landing phase of the gait cycle, maximum braking force slows the body down [10] and the associated sheering forces experienced at the foot can increase the likelihood of blisters [19] especially in longer distance races. No significant differences in maximum braking forces were found in this study, suggesting that even with a full water bladder, an increase in blisters is unlikely. There was a trend towards slightly larger (although not significant) propulsive forces as the weight of the backpacks increased. These findings were in line with those of Hsiang and Chang [20] who found significantly increased push-off rates with both increased loads and gait speeds. The loads in this current study were lower than the Hsiang and Chang study [20].

One interesting outcome of this study was the consistent maximum medial forces between backpack weight but the approximately 10 N decrease in lateral forces between the two lighter backpack weights (empty and 0.5 L) versus the two heavier backpack weights (1.5 L and 2.5 L). One aspect that may be attributed to the outcome of this and the other results found in this study may be the free movement of water in the bladder. Although it cannot be confirmed, the water in the pack may have aided in dampening some aspects of the GRF parameters. Most other studies related to backpack and gait analysis used solid material to load the packs. There may have been a dampening effect of the water on the GRF during the gait pattern.

Although no known studies have examined the effects of an additional liquid mass on GRF, wobbling mass models have shown that soft tissue motion relative to the underlying bone influences dynamic aspects of running [21]. Specifically, the addition of a spring-mass-damper system to a spring-loaded inverted pendulum model to simulate running shows that energy is dissipated due to the passive motion of soft tissue [22] and that increased stability is one of the effects of this dissipation [23].

Physiologically, Scheer [24] found no metabolic costs when using a 1.0 kg of added weight via water bottle, waist belt or backpack, running at an average speed of $3.3 \text{ m}\cdot\text{s}^{-1}$ ($11.8 \text{ km}\cdot\text{hr}^{-1}$), somewhat faster than the average speed in this study, but with weight equivalent to the backpack with 0.5 L of water. Scheer [25] did find significantly reduced metabolic costs after 20 min of running with a 3 kg and 6 kg pack that was equally distributed on the front and back, compared to a pack that was solely loaded on the back. Also, no significant changes in kinematic measures of running were found when carrying water by hand (454 g) or on the waist (676 g) [26].

During marathon and ultramarathon training and racing, the frequency of steps taken is high and therefore the musculoskeletal structures involved can become injured even with lower stresses [3]. These stresses come from a variety of sources both internal and external [27], though the combination of weight and running speed are key factors. Even with a slight increase in stress, such as the addition of a hydration pack, the musculoskeletal system can reach a stress–frequency relationship that over time will result in injuries. Increased magnitudes or volumes of impact forces, like those experienced during load carriage or running, are a major risk factor for overuse injuries [10,12].

Several limitations of this study should be noted. First, although not significant, there were differences in the running velocities across the four conditions, which may have

affected the outcome of the study. Furthermore, the packs were consistent with what a distance runner would wear, though these loads are relatively small. Finally, testing was performed in laboratory conditions with participants rested. The outcomes may be different in outdoor conditions and when participants are fatigued to different levels; these should be considerations for future studies.

Overall, this study showed a lack of increased GRF with increases in hydration pack weight and may likely be attributable to a combination of insufficient weight, wobbling of the water, and adjustments by the participants. However, these outcomes may be different when individuals have been running for a period, are running in outdoor conditions, and/or are starting to become fatigued. Therefore, runners and coaches should take the outcome of this study with caution. Still, based on the outcome of this study, it is believed that adding a hydration pack of up to 2.5 L (i.e., 3.2 kg) will not increase the likelihood of injuries, especially when the benefit of readily available hydration is considered.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data of this study are available on request from the corresponding author.

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