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The effect of increasing inertia upon vertical ground reaction forces and temporal kinematics during locomotion

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SUMMARY

The addition of inertia to exercising astronauts could increase ground reaction forces and potentially provide a greater health benefit. However, conflicting results have been reported regarding the adaptations to additional mass (inertia) without additional net weight (gravitational force) during locomotion. We examined the effect of increasing inertia while maintaining net gravitational force on vertical ground reaction forces and temporal kinematics during walking and running. Vertical ground reaction force was measured for 10 healthy adults (five male/five female) during walking (1.34 m s^{-1}) and running (3.13 m s^{-1}) using a force-measuring treadmill. Subjects completed locomotion at normal weight and mass and at 10, 20, 30 and 40% of added inertial force. The added gravitational force was relieved with overhead suspension, so that the net force between the subject and treadmill at rest remained equal to 100% body weight. Ground reaction forces were affected by the added inertial force, but not to the magnitude predicted by the increase in mass, suggesting that adaptations in motion occurred. Vertical ground reaction force production and adaptations in gait temporal kinematics were different between walking and running. Peak vertical impact forces and loading rates increased with increased inertia during walking, and decreased during running. As inertia increased, peak vertical propulsive forces decreased during walking and did not change during running. Stride time increased during walking and running, and contact time increased during running. The increased inertial forces were utilized independently from gravitational forces by the motor control system when determining coordination strategies.

Key words: biomechanics, locomotion, ground reaction force, inertia, gravity, weight, mass, human.

INTRODUCTION

During long-term space flight, astronauts experience losses in bone mineral density in addition to the loss of muscle (Schneider et al., 1995; LeBlanc et al., 2000; Iwamoto et al., 2005). Locomotive exercise is performed by astronauts, resulting in a ground reaction force (GRF) that may create bone strains hypothesized to be an osteogenic stimulus (Rubin and Lanyon, 1985). An external load is applied through a waist and shoulder harness that anchors the astronaut to the treadmill and acts to replace gravity. McCrory et al. (McCrory et al., 2002) suggest that achieving an external load equivalent to 100% of body weight is beneficial to generating GRF similar to those experienced in normal gravity. However, in actual microgravity conditions, increasing external loads may not be sufficient to recreate all components of GRF trajectories experienced in normal gravity (Schaffner et al., 2005).

Force is a product of mass and acceleration. The net GRF during locomotion will be equal to the force between the foot and ground necessary to support the body weight (gravitational force) and to accelerate the mass of the subject (inertial force) and can be expressed as: GRF=$m(\boldsymbol{g}+\mathbf{a})$, where m is the mass of the subject, $\boldsymbol{g}$ is the force of gravity, and $\mathbf{a}$ is the acceleration of the whole body center of mass (COM) (Munro et al., 1987). Therefore, the net GRF will be affected by gravitational and inertial components.

In microgravity, $\boldsymbol{g}$ is the external load returning the astronaut to the treadmill. The decreased GRF found by Schaffner et al. (Schaffner et al., 2005) could be due to reduced gravitational forces, altered locomotion mechanics, or a combination of these factors. However, if gravity and mechanics remain consistent, an increase in mass should result in an increase in GRF. Based on this framework, the decreased GRF that occurs as gravity is reduced could be compensated for with an increase in inertial mass if the mechanics of motion remain unchanged as inertial mass is added. More specifically, if the motion of the body does not change, the increase in GRF at a given gravitational level should be equivalent to the increase in mass.

The added inertial mass hypothesis can be tested in the laboratory using overhead suspension. Gravitational weight can be increased by adding inertial mass, while simultaneously applying an equal but opposite force to relieve the additional weight. Past researchers have examined the effect of increasing inertial and gravitational force upon walking and running.

Increasing inertial and gravitational force has been shown to increase metabolic cost and joint forces during walking (Griffin et al., 2003). Grabowski et al. (Grabowski et al., 2005) found that increasing inertia without increasing gravitational force during treadmill walking at 1.25 m s^{-1} resulted in an increased oxygen consumption, suggesting that the expenditure of metabolic energy used to overcome inertial forces is independent of that used to overcome gravitational forces. Chang et al. (Chang et al., 2000) found that during treadmill running at 3.0 m s^{-1}, an increase in inertia without a corresponding increase in gravitational force did not result in an increase in GRF, and Teunissen et al. (Teunissen et al., 2007) found no changes in net metabolic cost.

There have been no studies examining the effect of added inertial force (AIF) without adding gravitational weight on GRF during walking, and none examining walking and running using identical methodologies. Since metabolic costs were affected differently with AIF between walking and running, the mechanical adaptations to AIF may be locomotion mode dependent.

The purpose of the current investigation was to examine the effect of AIF while maintaining gravitational force on GRF during walking and running. Specifically, we hypothesized that there will be increases in GRF that accompany increased inertial mass while maintaining gravitational force that are equivalent to the increase in mass, but that the adaptations will differ between the two modes of locomotion. The results of this investigation may help to better explain the effects of inertial forces on locomotion independent of gravitational forces.

MATERIALS AND METHODS

Subjects

Ten experienced treadmill runners (five men and five women) volunteered to participate in this study (age 34.4±6.9 years, mass 68.4±11.7 kg; mean ± s.d.). All subjects were healthy and had previously passed a yearly United States Air Force Class III-equivalent physical examination. In addition, because the vest used for adding inertial mass to the subject had a maximum capacity of 38.1 kg, all subjects had to weigh less than 95.3 kg. This investigation was reviewed and approved by the NASA Johnson Space Center Committee for Protection of Human Subjects. Subjects provided written informed consent prior to participation in the study.

Instrumentation

Vertical GRF data were collected using a force-measuring treadmill (Kistler Gaitway, Amherst, NY, USA). GRF data were sampled at a rate of 481.2 Hz with two force plates beneath the running tread. Force plates were arranged so that one plate rested in front of the other. Each plate contained four piezoelectric load cells that measured vertical GRF and allowed for determination of the center of pressure.

Inertial force was added to each subject using a weighted exercise vest (X-Vest; Perform Better, Cranston, RI, USA). The vest had pockets located around the upper and lower trunk for the addition of weights. Each pocket was fitted with slots in which up to 21 individual 0.45 kg masses could be placed. Slots for weights were located on both inner sides of each pocket (10 on the outer side; 11 on the inner side). During trials, masses were added equally to the front and rear of the vest. The masses were always added to the inner-lower slots first, followed by inner-upper, outer-lower and outer-upper slots.

Gravitational force was maintained with an overhead unweighting system (H/P/Cosmos Airwalk, Nussdorf, Germany). The system provided a constant upward force *via* a pneumatic pump that unweighted subjects through use of a harness worn about the waist and thighs (Fig. 1).

Procedures

Prior to data collection, each subject participated in a familiarization session during which they had the opportunity to practice each test condition at each speed until they were comfortable. Subjects then completed one walking and one running data collection session within one week after the familiarization session. Walking trials occurred during a separate session from running trials. Seven days separated each session. The speed order for the data collection trials was randomized for each subject using a coin flip during the familiarization session.

Fig. 1. Data collection procedures showing the unweighting system and weighted vest.

Treatment randomization occurred independently for each speed. To assure that there was a balance of AIF conditions between subjects, a balanced Latin square random assignment was used (Portney and Watkins, 2000). The design allowed for a balance of treatment orders so that no two testing sequences were the same for different subjects within each speed. Each subject was randomly assigned a sequence from the table, with only one subject completing each specific order. Trial order assignment occurred separately for each speed. The subjects wore the unweighting harness during all conditions, including the 0% AIF trial.

Upon arrival at the laboratory, each subject was provided with standardized running shoes (Xccelerator TR; NIKE, Inc., Beaverton, OR, USA) and completed a general health questionnaire. Once the unweighting harness had been donned, the subject's weight was measured by the force treadmill. This weight was used to compute the amount of AIF required to achieve each condition.

Data were collected at two speeds during five AIF treatments. Subjects walked at 1.34 m s^{-1} and ran at 3.13 m s^{-1}. In addition to a control condition of no added inertial force (0% AIF), inertial force was added while body weight was maintained. We added an additional 10%, 20%, 30% and 40% of body weight and mass to each subject. For each AIF condition, the added weight was relieved with the unloading system so that the net force between the subject and treadmill remained equal to 100% body weight.

Subjects completed approximately one minute of treadmill locomotion at each AIF condition. Data collection began once the subjects had achieved a steady walking or running pace. Immediately following one minute of data collection, the weighted vest was removed and the unweighting harness was released. The subject then completed three minutes of walking at 1.34 m s^{-1} to eliminate any adaptation to gait that may have occurred during the test condition. The subjects were given additional rest of approximately three to four minutes until they felt that they were ready to continue with the next AIF condition.

Data processing

The first 10 strides of the left leg were analyzed in each one-minute trial. The left side only was analyzed with the assumption that gait kinematics were symmetrical within subjects (Karamanidis et al., 2003). The chosen epoch began with the first heel strike of the left foot and ended with the eleventh heel strike of the left foot. Data analyses were performed using software written in Visual Basic for Applications interfaced with Microsoft Excel 2003 SP1 (Redmond, WA, USA) and MATLAB Version 7.2.0.232 (R2006a) (Mathworks, Natick, MA, USA).

Custom software converted the output from each force sensor to vertical GRF and center of pressure location. Raw voltage data from the eight load sensors in the treadmill force platforms were transformed into forces using calibration factors. The total vertical GRF during each sample was then calculated as the sum of the vertical forces measured by each sensor. Center of pressure during each sample was determined relative to the force platform reference frame using the force outputs from each sensor along with the dimensions of the force sensors relative to one another. Center of pressure locations were used to determine which foot was in contact with the treadmill during each step.

Data analyses

The instance of heel strike for each stride was determined using GRF data according to the criterion of Chang et al. (Chang et al., 2000). An automated algorithm determined heel strikes as the samples at which a positive change in the force greater than 1 N s^{-1} occurred when the force magnitude was less than 100 N. The time of toe-off was computed in a similar manner. The toe-off sample was defined as the sample at which a negative change in the GRF less than 1 N s^{-1} occurred when the magnitude of the force was less than 100 N.

GRF data were used to find contact time, stride time, peak vertical impact force, loading rate, peak vertical propulsive force and impulse for each trial. All analyses were completed using raw GRF to ensure that peak values were not dampened. Visual inspection of each footfall was used to ensure that there were no anomalous data.

Contact time was the length of time that the left foot was in contact with the treadmill during each stride and was calculated as the duration between heel strike and toe-off for each left footfall. Stride time was the length of time between successive heel strikes of the left foot. Peak vertical impact force was the magnitude of the first distinct peak in the GRF trajectory. Peak vertical propulsive force was the magnitude of the second distinct peak. Loading rate was the peak vertical impact force divided by the time between heel strike and time of peak vertical impact force. The impulse for each footfall was computed as the integral of the GRF trajectory over contact time. Peak vertical impact force, loading rate, peak vertical propulsive force and impulse were all normalized to actual body weight found prior to the data collection session to allow for inter-subject comparisons.

Table 1. Contact time and stride time for each added inertial force (AIF) condition for walking and running

	Contact time (s)		Stride time (s)	
Treatment	Walk	Run*	Walk*	Run*
0% AIF	0.64±0.04	0.25±0.02	1.05±0.06	0.72±0.05
10% AIF	0.63±0.04	0.26±0.02[a]	1.05±0.06	0.72±0.06
20% AIF	0.63±0.04	0.26±0.02[a]	1.04±0.06	0.73±0.06
30% AIF	0.63±0.04	0.27±0.02[a,b]	1.05±0.06	0.73±0.04
40% AIF	0.64±0.04	0.28±0.02[a,b,c]	1.06±0.06[c]	0.75±0.05[a,b,c]

Values are means ± s.d. Note: *significant main effect of load, $P<0.05$; [a]different from 0% AIF; [b]different from 10% AIF; [c]different from 20% AIF.

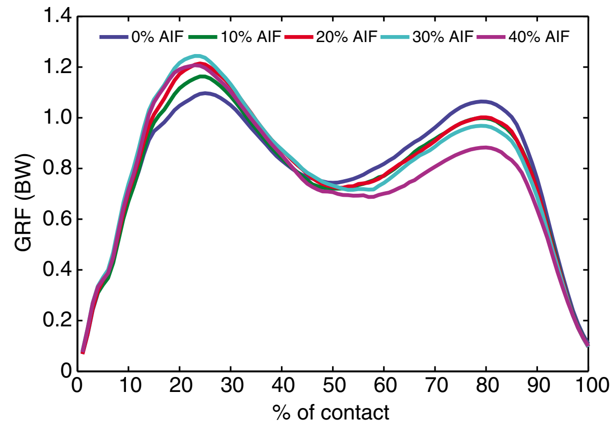

Fig. 2. Mean ensemble ground reaction force (GRF) trajectories during walking at all added mass (AM) levels. AIF, added inertial force; BW, body weights.

Statistical analysis

A trial mean for each dependent variable was calculated from all 10 strides. Statistical analyses were conducted utilizing NCSS 2004 statistical software (Kaysville, UT, USA). Trial means for all dependent variables were tested using repeated measures analysis of variance (ANOVA) with AIF level as a single factor. Walking and running were analyzed separately because they are two different tasks that require different motor patterns. Tukey-Kramer Multiple Comparisons tests were used to determine differences between AIF levels when a significant main effect was found. Differences were considered to be statistically significant when $P<0.05$.

RESULTS

Temporal parameters

Contact time was affected differently by AIF between walking and running. Contact time did not change during walking, but did increase with added inertia during running. Stride time was affected by inertia during both walking and running for the largest AIF condition (Table 1).

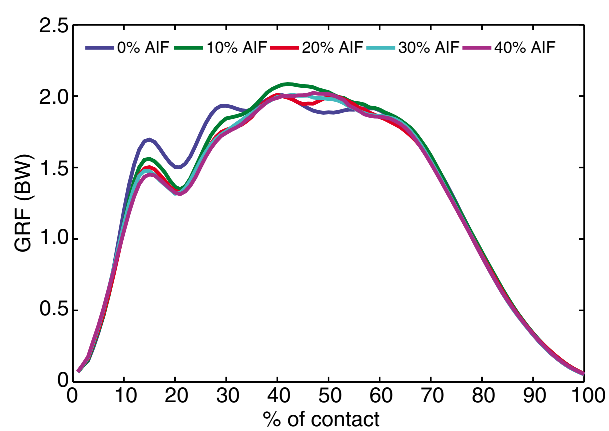

Fig. 3. Mean ensemble ground reaction force (GRF) trajectories during running at all added mass (AM) levels. AIF, added inertial force; BW, body weights.

Table 2. Peak vertical impact force and loading rate for each added inertial force (AIF) condition for walking and running

	Peak vertical impact force (BW)		Loading rate (BW s^{-1})	
Treatment	Walk*	Run*	Walk*	Run*
0% AIF	1.13±0.05	1.77±0.18	7.41± 0.62	46.39±9.52
10% AIF	1.19±0.06	1.64±0.15	8.08±0.51	41.40±7.21
20% AIF	1.24±0.10[a]	1.55±0.17[a]	8.79±0.94[a]	37.48±5.12[a]
30% AIF	1.28±0.10[a,b]	1.55±0.15[a]	9.50±1.40[a]	37.39±8.27[a]
40% AIF	1.24±0.07[a]	1.48±0.14[a,b]	9.02±1.17[a,b]	34.20±5.91[a,b]

Values are means ± s.d. Note: *significant main effect of load, P<0.05; [a]different from 0% AIF; [b]different from 10% AIF; [c]different from 20% AIF. BW, body weights.

Table 3. Peak vertical propulsive force and impulse for each added inertial force (AIF) condition for walking and running

	Peak vertical propulsive force (BW)		Impulse (BW ms)	
Treatment	Walk*	Run	Walk	Run*
0% AIF	1.10±0.04	2.18±0.13	524.21±48.52	328.77±22.63
10% AIF	1.02±0.03	2.20±0.13	509.19±41.13	336.24±21.73
20% AIF	1.02±0.08	2.17±0.24	517.92±56.84	333.34±23.81
30% AIF	0.99±0.10[a]	2.16±0.12	520.62±70.95	341.72±27.36
40% AIF	0.90±0.09[a,b,c,d]	2.15±0.15	496.06±50.19	345.78±31.25[a]

Values are means ± s.d. Note: *significant main effect of load, P<0.05; [a]different from 0% AIF; [b]different from 10% AIF; [c]different from 20% AIF; [d]different from 30% AIF. BW, body weights.

Ground reaction forces

Normalized, ensemble averaged vertical GRF trajectories for walking and running over all trials for all subjects are shown in Figs 2 and 3. In general, the trajectories of the GRF curves appeared to be a similar shape to one another regardless of the AIF level. During walking, peak vertical impact forces and loading rate increased and peak vertical propulsive forces decreased with the addition of inertial force (Tables 2 and 3). There was no effect of additional inertial force upon impulse during walking.

During running, peak vertical impact forces and loading rate decreased as inertial force was added. There was no effect of AIF during running for peak vertical propulsive force. The impulse during the 40% AIF condition was greater than during the 0% AIF condition.

DISCUSSION

We studied how locomotion temporal kinematics and ground reaction forces were affected by increasing inertial force (mass) while maintaining gravitational force (weight). Our study was the first to investigate walking and running with increased inertial force without increasing gravitational force using identical methodology for each locomotion type. We observed that the adaptations during walking were different from those during running. Contact time was unaffected during walking but increased with AIF during running. Stride time adaptations were similar for both modes of locomotion. The addition of inertial force resulted in increased peak vertical impact GRF and loading rates during walking but decreased peak vertical impact GRF and loading rates during running. By contrast, peak vertical propulsive GRF during walking decreased with AIF but did not change during running. Impulse was maintained during walking and was only affected during the highest AIF condition during running.

Ground reaction force is a product of mass, acceleration due to gravity, and acceleration of the COM due to motion. Gravitational forces are those that are associated with weight, while inertial forces are those associated with the acceleration of a mass. Our experiment used overhead suspension to keep gravitational forces constant as mass increased. Therefore, unless adaptation in motion occurred, an increased mass should result in an equal increase in GRF.

Locomotive adaptations to AIF differ between walking and running

We found increases in the impact GRF with AIF during walking, but of lesser magnitude than could be explained by the increase in mass. In addition, propulsive GRF decreased with AIF while impulse was not affected. During running, impulse was also unchanged except at the highest AIF by decreasing impact GRF while maintaining propulsive GRF and increasing contact time.

The impulse–momentum relationship states that the change in momentum of the COM will be equal to the impulse applied. Momentum is the product of mass and change in velocity. Therefore, for a given impulse, an increase in mass will result in a decrease in the change in velocity during the time that the force is applied. The change in velocity of the COM during stance is equal to the final upward velocity minus the initial downward velocity. Since impulse did not change with AIF during either mode of locomotion, the net change in velocity of the COM during contact must have decreased. It is not clear if the impact velocity decreased, the takeoff velocity decreased, or if both were modified. However, the different responses of the GRF to the AIF indicate that adaptations in motion differ between walking and running but may be intended to produce the same result.

During walking, subjects maintained contact time and stride time, except during the most extreme loading condition (40% AIF), where stride time increased. Increases in peak impact GRF and loading rate were less than predicted and were coupled with a decrease in propulsive GRF. The impact GRF increases continued up to 30% AIF and may explain the increases in metabolic costs with added inertia reported by Griffin et al. (Griffin et al., 2003) and Grabowski et al. (Grabowski et al., 2005).

Because impulse did not change with AIF, the net change in the COM velocity during stance decreased. During the impact phase of walking, the increase in GRF with AIF, although less than predicted, decelerated the COM downward at a greater rate than when unloaded or loaded to lesser mass. However, because the increase in GRF was less than the increase in mass, the net change in downward velocity of the COM must have decreased. It is probable, therefore, given that the final downward velocity of the COM was zero, the impact COM velocity decreased with AIF. During the second half of stance, the decrease in propulsive GRF acting over the same time period resulted in a COM upward takeoff velocity that was slower than that occurring with less AIF. The net change, however, decreased given the increase in mass.

During running, the impact GRF decreased with AIF. The reduction in GRF coupled with the increase in mass resulted in the reduction of the COM downward deceleration when compared to unloaded conditions. Similar to walking, it is probable that the decrease in net change of COM velocity was caused by a decrease in COM velocity at impact. Since the propulsive GRF of running did not change, but mass increased, the upward acceleration of the COM was also less than during when unloaded, resulting in a lower COM takeoff velocity. The lack of increase in GRF with AIF may also explain the lack of increase in the net metabolic cost of running reported by Teunissen et al. (Teunissen et al., 2007).

Running contact time increased with AIF. The increase in contact time allowed for the maintenance of impulse by allowing the GRF to act upon the COM for a longer time. The increase in contact time with no change in stride time suggests that subjects spent less time airborne as inertial forces were added. Less flight time is consistent with the explanation that impact and takeoff COM velocities decreased.

Since heel strike and takeoff velocities decreased with AIF, it is probable that the trajectory of the COM changed as inertial forces increased. During walking, the trajectory of the body's COM can be approximated as an inverted arc (Alexander, 1976; Lee and Farley, 1998). The COM is highest during single-limb support and lowest during double-limb support (Chou et al., 2001). The decrease in takeoff velocity will result in a lower maximum height of the COM, causing the arc to become flatter. The downward displacement during double-support will be dependent upon the upward force applied and the time the impact force acts. The flatter trajectory would also decrease the vertical downward velocity of the COM at heel strike, explaining the lower than expected GRF. While the same result occurs for walking and running, the manner in which the subjects manipulate the GRF differs for each locomotion mode.

For both speeds, significant AIF effects were detected at 40% AIF, our highest inertial condition tested, for many of our dependent variables. Stride time increased for both walking and running, and there was a slight decrease in impact forces and loading rates from 30 to 40% AIF. A threshold effect may occur at increases in inertial forces greater than 30% of normal. The threshold might occur as a protective mechanism against injury, since increased loading could increase the risk of bone or muscle damage.

Adaptations to gravitational and inertial forces

Our findings suggest that adaptations during locomotion to altered inertial forces differed from adaptations to altered net gravitational forces. We found that adding inertial force while maintaining gravitational force did not appreciably affect walking temporal kinematics, while during running, contact time and stride time increased. Donelan and Kram (Donelan and Kram, 1997) found that contact time and stride time decreased during walking with decreased gravitational force while maintaining inertial force. Griffin et al. (Griffin et al., 1999) and Finch et al. (Finch et al., 1991) also found that stride time did not significantly change during walking. He et al. (He et al., 1991) and Millslagle et al. (Millslagle et al., 2005) found that, during running, contact time decreased and stride time increased. Farley and McMahon (Farley and McMahon, 1992) found no increases in contact time with the reduction of gravity during running. Both Chang et al. (Chang et al., 2000) and Newman et al. (Newman et al., 1994) found decreases in peak vertical GRF during running, which makes sense since there is a reduced need to decelerate and accelerate the COM.

Others have studied the effect of increasing gravitational and inertial forces on locomotion. Contact time increased and stride time decreased during walking and running (LaFiandra et al., 2003; Chang et al., 2000). Griffin et al. (Griffin et al., 2003) found increases in peak GRF during walking, and Chang et al. (Chang et al., 2000) found similar increases in GRF during running. The increase in GRF is intuitive because of the need to decelerate and accelerate a larger mass during stance.

Taken together, these studies suggest that an increase in inertial and gravitational force results in kinematic adaptations during walking and running that include increased contact time, decreased stride times, and increased GRF. Decreases in gravitational force with constant inertia resulted in decreased contact time, no change in stride time, and decreased GRF. Contact time and vertical GRF during walking and running may be directly influenced by gravitational forces. Stride time, however, may only adapt when gravitational force is decreased.

Our results suggest that, during walking, gravitational force is a critical factor utilized for selection and execution of the gait pattern, although adaptations to increased inertia do occur. However, during running, inertial forces play a larger role in the control process. Bernstein (Bernstein, 1967) theorized that motion requires the interaction between the central nervous system and the state of the position, velocity and weight of the affected limbs. Our findings are consistent with this theory, because if gravitational forces were the main input when determining the motion patterns during locomotion, no adaptations to increased inertial force on the trunk should occur, and GRF will increase with AIF as predicted by mechanical equations of motion.

Limitations

While our original question was to investigate a potential enhancement to exercise countermeasures performed in microgravity, we tested our hypothesis in normal gravity using an overhead suspension system. Our testing location allowed data collection from multiple subjects in a controlled environment. The subjects could familiarize themselves with the testing environment, and testing sessions were not limited by factors that influence experiments in microgravity, such as limited sample size and availability to collect data. However, because we tested subjects in normal gravity, it is possible that our results would differ in a microgravity environment. The AIF were applied in a manner that could be used during spaceflight. However, in our experiment, the limbs were subject to normal gravity, and the gravitational forces resulting from the AIF were reduced by suspension with a harness. The harness could have influenced the adaptations that we measured.

It must be noted that we were unable to measure changes in horizontal forces, potentially affecting our results. It was impossible to determine if the reduction in vertical GRF was accompanied by an increase in horizontal GRF. If this were to occur, the magnitude of the GRF would be unaffected, but the orientation of the GRF vector would change. This could be another explanation for the reduced vertical GRF with increased inertial forces. However, Chang et al. (Chang et al., 2000) found that during running with increased inertial forces, the orientation of the GRF vector did not change. Since our experimental setup was similar to theirs, we have no reason to believe that a change in GRF vector occurred. In addition, given that we tested all subjects in the same manner, we believe any effects of the horizontal GRF would be systematic. Chang et al. (Chang et al., 2000) did find an increase in horizontal impulse when inertial forces were increased and gravitational forces were held constant. However, the increases were not linearly related to the amount of added inertia.

Applications to spaceflight exercise

One of our intents in this investigation was to determine if locomotive exercise performed in reduced gravity could be enhanced with the addition of inertial force. We hypothesized that adding inertial force may help to increase the vertical GRF that occurs during treadmill exercise, and thus enhance the current countermeasure. Our findings in normal gravity suggest that the addition of inertial force may increase walking GRF during space flight. However, adaptations in the gait pattern during running would likely mitigate increases in GRF. Confirmation of these suppositions could be gained only during a microgravity experiment.

Conclusion

We investigated the effects of adding inertial force while maintaining gravitational force upon temporal kinematics and GRF during walking and running. Perhaps the most interesting finding is that the adaptations to AIF during walking were different than during running, suggesting that walking and running should be thought of as two distinct tasks, rather than alternate forms of locomotion. However, the control strategies utilized as a result of increased inertial forces may attempt to maintain impulse by adapting motion kinematics. Furthermore, changes in motion that occur due to increases in inertial forces are not the same as those occurring due to increases in gravitational forces. Researchers should differentiate between adding mass and weight during biomechanical investigations.

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