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Original article

Increased hip flexion gait as an exercise modality for individuals with obesity

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Abstract

Purpose: Exercise is a critical element for the management of body weight and improvement of quality of life of individuals with obesity. Due to its convenience and accessibility, running is a commonly used exercise modality to meet exercise guidelines. However, the weight-bearing component during high impacts of this exercise modality might limit the participation in exercise and reduce the effectiveness of running based exercise interventions in individuals with obesity. The hip flexion feedback system (HFFS) assists participants in meeting specific exercise intensities by giving the participant specific increased hip flexion targets while walking on a treadmill. The resulting activity involves walking with increased hip flexion which removes the high impacts of running. The purpose of this study was to compare physiological and biomechanical parameters during a HFFS session and an independent treadmill walking/running session (IND).

Methods: Heart rate, oxygen consumption (Vo_2), heart rate error, and tibia peak positive accelerations (PPA) were investigated for each condition at 40% and 60% of heart rate reserve exercise intensities.

Results: Vo2 was higher for IND despite no differences in heart rate. Tibia PPAs were reduced during the HFFS session. Heart rate error was reduced for HFFS during non-steady state exercise.

Conclusion: While demanding lower energy consumption compared to running, HFFS exercise results in lower tibia PPAs and more accurate monitoring of exercise intensity. HFFS might be a valid exercise alternative for individuals with obesity or individuals that require low-impact forces at the lower limbs.

Keywords: Exercise; Heart Rate; Vo2; Tibia accelerations; Running.

Introduction

Obesity has been significantly and consistently associated with persistent pain complaints (Silverwood et al. 2015). Lower limb pain is one of the locations of pain most commonly reported with individuals with obesity being 2.2 to 4 times as likely as underweight and normal-weight individuals to experience this type of pain (Hitt et al. 2007). Additionally, individuals with a BMI >30 kg/m^2 have been described as 6.8 times more likely to develop knee osteoarthritis compared to healthy weight controls, or at a 2.63 (95% confidence intervals, 2.28 to 3.05) pooled odds ratio for developing osteoarthritis compared to healthy weight controls (Coggon et al. 2001; Blagojevic et al. 2010). Underlying mechanisms explaining these relationships are related to both the increased mechanical stress caused by extra weight on the joints as well as inflammatory effects of elevated cytokines and adipokines that affect cartilage degradation (Coggon et al. 2001). Therefore, in addition to the increased risk of chronic disease (e.g. heart disease, stroke, diabetes, and cancer) associated with obesity, individuals with obesity might experience pain, stiffness, and decreased range of motion of the joints, leading to a loss of functional independence and reduced mobility (Leveille et al. 2004), contributing to a cycle of weight gain that affects the individual's quality of life.

Exercise is a critical element for the management of body weight, and improvement of function and quality of life of individuals with obesity (Shaw et al. 2006; Riebe et al. 2017). The American Heart Association, the Centers for Disease Control and Prevention, and the American College of Sports Medicine (ACSM) all recommend regular exercise of moderate intensity for general health benefits. In individuals with obesity, those who participated in exercise interventions alone have been shown to have reduced systolic and diastolic blood pressure, cholesterol, triglycerides, and fasting serum glucose (Shaw et al. 2006). Previous studies have also demonstrated that exercise improves risk factors for cardiovascular disease in overweight or obese adults (Hu et al. 2000). Moreover, a positive relationship has been established between the health benefits resulting from exercise and the intensity of that exercise (Riebe et al. 2017; Gillen and Gibala 2018). For example, for individuals with obesity, ACSM guidelines recommend that initial intensity of exercise should be moderate (40%-59% VO_2 reserve (VO_2R) or heart rate reserve (HRR)) but should progress to vigorous ($\geq$ 60% VO_2R or HRR) for greater benefits (Riebe et al. 2017).

Running is a convenient and accessible exercise modality commonly used to meet aerobic exercise guidelines. However, the weight-bearing component during high impacts of this exercise modality might limit the effectiveness and efficiency of exercise interventions in individuals with obesity (Crowell and Davis 2011; Gessel and Harrast 2019). During running, obesity has been associated with alterations of dynamic knee loading, higher tibia peak positive acceleration at ground impact, and higher average and instantaneous vertical ground reaction force loading rates that have been shown to increase the risk of injury in the knees in individuals with obesity (Harding et al. 2016; Tirosh et al. 2019). When compared with healthy-weight individuals, individuals with obesity have altered kinematic and kinetic variables at the hip and knee that may result in mechanical inefficiencies, higher joint moments, and ground reaction forces; potentially increasing the risk of joint degradation and poor joint health (Bowser and Roles 2021; Spech et al. 2022). Moreover, children with obesity have been shown to develop different running patterns with increased foot pressure, which may predispose them to foot pain and overuse injuries (Rubinstein et al. 2017). This is exacerbated when trying to increase exercise intensity, by running faster, for optimal health benefits (Ni 2016).

The current study evaluates a novel exercise modality that addresses the weight-bearing limitations of running. In this exercise modality, individuals walk on a treadmill and increase intensity (defined by metabolic cost) by increasing hip flexion while walking and actively controlling the impact of the foot on the treadmill. The resulting exercise mode is an open chain movement that involves: 1) the whole body (movement of the upper limbs is natural and required for balance); 2) coordination between the body segments; 3) large hip and knee range of motion, and 4) increased movement variability. To assist the individual in performing the exercise at the target exercise intensity and with low foot impact forces (tibia peak positive accelerations and ground reaction forces), a hip flexion feedback system (HFFS) was developed. The HFFS assists the individual in controlling the intensity of the exercise by monitoring the individual's heart rate and calculating, in real-time, the appropriate maximum hip flexion targets during treadmill walking (based on the difference between the actual heart rate and the target heart rate). The HFFS will also monitor vertical lower leg kinematics and inform the user when downward velocities during terminal swing phase are too high.

The purpose of this study was to compare a new exercise modality resulting from using the HFFS to standard treadmill walking/running exercise at 40% and 60% heart rate reserve (HRR). We investigated oxygen consumption (Vo_2) to compare the metabolic efficiency between modalities, and tibia peak positive accelerations to compare the risk of lower extremity injury. Therefore, we hypothesized that 1) treadmill walking/running exercise and HFFS exercise would have different metabolic cost and 2) HFFS exercise would result in lower (magnitude and frequency) tibia peak positive accelerations than treadmill running.

Materials and Methods

2.1 Participants

Twenty individuals with obesity (12M, 8F; age: 24.3 ± 4.9 years; height: 172 ± 8.9 cm; body mass: 109.5 ± 21.3 Kg; BMI: 36.7 ± 6.1) participated in this study. The level of physical activity was assessed using the International Physical Activity Questionnaire (IPAQ) (4 high, 8 moderate, 8 low). This study was approved by the University of Southern Mississippi Institutional Review Board. Participants were informed of the benefits and risks of the investigation before providing written consent.

2.2 The hip flexion feedback system

The principles of operation of the HFFS have been described in a previous study (Oliveira and Chiu 2022). The HFFS was developed using MATLAB (The Mathworks, Natick, MA) and the MTW Devkit (Xsens Technologies BV, Enschede, Netherlands) programming interface. The system uses seven inertial measurement units (IMUs) (Xsens Technologies BV, Enschede, Netherlands) to measure hip flexion angles, tibia axial accelerations, and wrist accelerations. A Polar Verity Sense arm strap monitor (Polar Electro Oy, Kempele, Finland) was used to measure heart rate. During treadmill walking, a screen placed in front of the treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) displayed information relative to the maximum hip flexion for each stride, the target for maximum hip flexion, the tibia axial accelerations, and arm swing linear accelerations (Fig. 1). Target maximum hip flexion was calculated using a Proportional-Integral-Derivative (PID) control loop mechanism (Åström and Hägglund 1995) that uses the target heart rate and actual heart rate as input parameters. Therefore, if the heart rate error was positive (target heart rate > actual heart rate) the system would increase the maximum hip flexion target; if the heart rate error was negative (target heart rate < actual heart rate) the system would reduce the maximum hip flexion target.

Tibia axial accelerations were calculated using an IMU (Xsens Technologies BV, Enschede, Netherlands) aligned in the long axis of the participant's tibia attached to the anteromedial aspect of the distal tibia using double-sided adhesive tape (German Brown, Walker Tape, UT, USA) and a Velcro strip (Crowell and Davis 2011; Tirosh et al. 2017, 2019). While using the HFFS, a 3g threshold was set to maintain participants closer to typical walking PPA values and below typical jogging/running values (Lafortune 1991; Montgomery et al. 2016). Feedback on arm swing linear accelerations was also given to promote arm movement, and participants were asked to maintain the arm swing indicators at "green" (indicating an appropriate level of arm-swing) by moving their wrists at a minimum peak linear acceleration calculated during the baseline trial. The wrist peak linear acceleration was calculated as the average peak linear acceleration of the wrists across the first 30s of the baseline trial. Therefore, exercise intensity is not only controlled by modifying the maximum hip flexion target during the exercise, but also by maintaining sufficient arm swing; all while limiting peak tibial accelerations (Oliveira and Chiu 2022).

2.3 Experimental Procedures

Participants visited the laboratory on two occasions at least one day apart. An exercise modality, HFFS or independent treadmill walking/running (IND), was randomly assigned to each visit. During HFFS exercise, participants were instructed to walk on the treadmill following the movement targets displayed on the screen (as described in the previous section). During the IND session, participants were instructed to control treadmill speed (*ad libitum*) to meet a specific target heart rate. Each exercise session involved a baseline measurement at preferred walking speed (5 minutes), two seven-minute trials at 40% heart rate reserve (HRR 40_1 and HRR 40_2, respectively), and two seven-minute trials at 60% HRR (HRR 60_1 HRR 60_2, respectively). HRR was calculated as the difference between the estimated maximal heart rate and the resting heart rate. Maximal heart rate was estimated using the 220-age formula (Fox III and Naughton 1972), and resting heart rate was measured using the heart rate monitor after at least four minutes of seated rest at the beginning of the visit. A 3-minute recovery period, during which the participant was sitting, followed each exercise trial and baseline trial. In the first visit, testing commenced with the familiarization of walking on the treadmill while selecting a preferred walking speed (PWS) which was used for all HFFS testing.

Before starting the exercise, a static calibration step was used to determine the zero position for hip flexion, and a dynamic calibration was used to determine the maximum hip flexion at PWS for each participant. During dynamic calibration, participants walked on the treadmill at PWS and were instructed to ‘lift their knees as high as possible while walking’ to achieve maximum hip flexion. This step was used to set the upper and lower limits for the hip flexion target display during HFFS training. The feedback interface was then introduced and explained. Participants were introduced to the visual display and were told what movement related information was being given by each indicator. After this introduction, participants were allowed to practice with the device until the association between the feedback cues and the corresponding movement features was sufficiently clear. Energy expenditure was evaluated from oxygen consumption measured during the exercise and recovery using a breath-by-breath portable metabolic analyzer (K5, COSMED, Rome, Italy).

2.4 Data Analysis

Feedback Error (FE) was calculated as the mean across the trial of the absolute errors between the target maximum hip flexion angle and the actual maximum hip flexion angle. FE was used as an indication of the participants' compliance with the hip flexion targets.

Heart rate error (HR_{err}) was calculated as the absolute error between the target heart rate (HR_{target}) and the actual heart rate.

The percentage of strides that resulted in tibia peak accelerations above 3g during each exercise trial was calculated ($T_{PPA\%}$). The mean peak positive acceleration (T_{PPA}) was calculated as the mean tibia PPA across all recorded strides for both sides for each trial above 3g. We have only included in our analysis T_{PPA} above 3g because this represents the magnitude typically reported during running (Lafortune 1991; Sheerin et al. 2019) that might represent an increased risk of injury (Crowell and Davis 2011). Values below 3g are typically associated with walking (Lafortune 1991; Tirosh et al. 2019). Additionally, 3g also represents the threshold for the tibia PPA feedback provided to the participants (Fig. 1), which might limit the possibility for participants to detect changes in tibia PPA below and above this value.

Vo_2, CHO%, FAT% , and HR, were calculated for baseline, non-steady state at 40% HRR and 60%HRR, and steady-state at 40% HRR and 60%HRR. For the 40%HRR trials and 60%HRR trials, the means across the two trials (HRR 40_1, HRR 40_2, and HRR 60_1, HRR 60_2) were used.

2.5 Statistical Analysis

A paired sample t-test was used to test for differences between exercise modality (HFFS and IND) at each intensity (baseline, HRR 40, HRR 60) for $T_{PPA\%}$, T_{PPA}, HR, HR_{err}, VO_2, CHO%, and FAT%. For HR, VO_2, CHO%, and FAT%, differences between exercise modality at non-steady (0 – 4min) and steady (4 – 7min) states were also tested. The Shapiro-Wilk Test was used to test the normality of the samples. For the tests where normality was violated, Wilcoxon Signed Ranks tests were used. Values that were more than 1.5 times the interquartile rage away from the upper quartile were considered outliers. Cohen's d was used to calculate effect sizes for parametric tests. Z divided by the square root of the sample size (r) was used to calculate effect sizes from the Wilcoxon Signed Ranks tests (Fritz et al. 2012). A significance level of 0.05 was used for all statistical testing.

Results

The average FE across sides and intensities was below 10% (right side at 40% HRR: 6.9 ± 4.5%; left side at 40% HRR: 7.0 ± 3.7%; right side at 60% HRR: 7.3 ± 5.5%; left side at 60% HRR: 7.3 ± 5.3%).

V_{O2} was higher for IND compared to HFFS during HRR 40% at steady state (p=0.014, r=0.56), and 60% HRR at non-steady state (p=0.019, r=0.54) and steady state (p=0.002, r=0.69). No differences between exercise modalities were observed for HR, CHO, and FAT.

IND $T_{PPA\%}$ was higher than HFFS $T_{PPA\%}$ during HRR 40% (p=0.003, d=16.2) and HRR 60% (p<0.001, d=28.8). Additionally, IND T_{PPA} were larger than HFFS T_{PPA} during HRR 60% (p=0.017, r=0.53).

HRerr was higher for IND during HRR 40% (p=0.008, r=0.60) and HRR 60% (p=0.017, r=0.54) at non-steady state.

Discussion

The present study introduces a new exercise modality for individuals with obesity that uses increased hip flexion targets during treadmill walking to increase exercise intensity. We hypothesized that this novel exercise modality would elicit similar heart rates and energy expenditures to running while resulting in lower peak tibia axial accelerations. As will be discussed in the following sections, this hypothesis is mostly supported by our findings.

As outlined in Table 1, relative oxygen consumption (Vo_2) was significantly lower during both HFFS trials compared to the IND trials, and no significant differences in substrate utilization (CHO% or FAT%) were observed between trials. When the final three minutes of each exercise bout were analyzed separately (allowing for an evaluation of steady-state responses), these differences appeared to be mediated by the slow-component of Vo_2 kinetics (Table 1) (Jones et al. 2011). While, at first, this may seem to indicate that the HFFS modality is less metabolically demanding compared to simple walking and/or running, it is also important to recognize that these Vo_2 responses were recorded at the same absolute HRR value. Therefore, this finding is more indicative of an exaggerated heart rate response for the same level of metabolic work. The authors consider a few mechanisms that could mediate such a response.

First, the movement patterns associated with the HFFS exercise trial are likely unfamiliar to participants, which may result in poorly coordinated movements and an increase in cortical activation during the HFFS trials. This notion is supported by prior evidence that performing complex motor tasks with the non-dominant hand elicits bilateral cortical activation, whereas performing the same task with the dominant hand elicits unilateral cortical activation only (Lee et al. 2019). Moreover, others have reported convincing evidence that cortical activation patterns are significantly altered during the performance of unfamiliar tasks (Schneider et al. 2009). These increases in cortical activation may lead to concurrent increases in central command, a feedforward neural mechanism known to increase heart rate and blood pressure during exercise (Green et al.

2007; Fisher et al. 2015). This may, in part, explain the augmented heart rate - Vo_2 relationship observed in the present study.

Secondly, considering that the HFFS exercise modality is designed to increase hip flexor moments and decrease knee extensor moments compared to traditional walking or running, this augmented heart rate response (relative to Vo_2) may also be explained by an increase in the relative oxygen cost of the smaller hip flexor muscles (compared to the larger knee extensors). Specifically, metabolic perturbations within skeletal muscle are known to activate metabosensitive group IV muscle afferents (Rotto and Kaufman 1988; Jankowski et al. 2013), which engage the afferent exercise pressor reflex (Fisher 2014). This response occurs in a dose-dependent manner (Harms et al. 2016), and even small muscle mass exercise (i.e., isometric handgrip) can elicit considerable increases in heart rate and blood pressure (Badrov et al. 2016). Therefore, if the same relative Vo_2 is achieved from a smaller volume of muscle, this may result in increased engagement of the exercise pressor reflex within that muscle, thus augmenting the heart rate responses to the same level of metabolic work.

Another possible explanation for the difference in Vo_2 might be related to differences in anaerobic involvement between the two modalities. This argument has been presented in the scientific literature to describe high-intensity intermittent exercise, and although we would not classify HFFS as high-intensity exercise, it is an unfamiliar way of partaking in exercise. Specifically, HFFS utilizes lower limb and core muscles not often exploited in day-to-day activity, and thus may demand a higher anaerobic component in the beginning/learning phase of the exercise. Therefore, the authors believe the slight difference in Vo_2 could be accounted for (or at least minimized) if both aerobic and anaerobic energy expenditures were calculated (Scott and Fountaine 2013). It should be noted that CHO and FAT utilization during IND and HFFS exercise was non-significantly different (HFFS 40% NST vs IND 40% NST: $p = 0.576$, 95% CI [-11.2, 6.4], $d = 0.127$; HFFS 40% ST vs IND 40% ST: $p = 0.285$, 95% CI [-13.4, 4.2], $d = 0.246$; HFFS 60% NST vs IND 60% NST: $p = 0.088$, 95% CI [-13.4, 1.0], $d = 0.402$; HFFS 60% ST vs IND 60% ST: $p = 0.461$, 95% CI [-10.5, 4.9], $d = 0.168$). These data may serve as useful pilot data for future studies investigation the differences in relative substrate utilization using HFFS, which can be related to aerobic and anaerobic energy expenditures. Also, it should be stated that although HR was the same between HFFS and IND conditions, variables that could have affected the HR of the participants between sessions were not controlled for and therefore HR (in this case HRR, calculated separately for each session) may not be the most accurate determinate of exercise intensity between the two sessions/exercise interventions. Although heart rate is a good predictor of exercise intensity, the relationship between HR and Vo_2 is individualized based on a variety of factors (such as modality) and the relationship between the two should be determined for each person to accurately prescribe exercise intensity based on HR alone (Juul and Jeukendrup 2003). Regardless of the mechanisms responsible for the augmented heart rate - Vo_2 relationship during the HFFS trial, HR_{err} was consistently lower for the HFFS exercise compared to running during non-steady state. This indicates that the HFFS was able to assist participants in meeting and maintaining exercise intensities more accurately than the individuals exercising independently. It is reasonable to think that individuals would improve their HR_{err} if participating in more exercise sessions, as they would be able to more accurately determine the walking/running speeds that would meet specific exercise intensities. However, individuals with obesity are typically unfamiliar with exercise prescription and might require assistance in the introduction to exercise protocols to facilitate adhesion to the guidelines. Therefore, HFFS might provide an added benefit in terms of assisting individuals unfamiliar with treadmill exercise in controlling exercise intensities and meeting the recommended exercise guidelines.

Peak Tibia axial accelerations were lower for HFFS compared to running (IND). This was indicated by the percentage of steps that recorded tibia PPAs above our threshold ($T_{PPA\%}$), and the magnitude of the accelerations recorded (T_{PPA}). The threshold value for peak positive tibia accelerations used in the present study was 3g. This value is consistent with the lower values typically observed during running (Sheerin et al. 2019). Therefore, when using the HFFS, participants were directed using visual feedback to maintain their tibia PPA at values associated with walking. HFFS $T_{PPA\%}$ was reduced at all exercise intensities compared with independent exercise. This is particularly important at the 60% HRR intensity, where more than 50% of the strides during the 7-minute IND bouts detected tibia PPA above 3g (average HFFS $T_{PPA\%}$ was approximately 10%) (Fig. 2). Additionally, the T_{PPA} observed during the 60% HRR intensities were higher for running compared to the HFFS modality (Fig. 3). The magnitude and the repetitive nature of the impacts associated with running, have been linked to the pathophysiology of running injuries (Milner et al. 2006; Tenforde et al. 2020). Those mechanisms are particularly important in individuals with obesity. Therefore, the differences in tibia PPAs observed in this study suggest that the HFFS exercise modality might be a safer option for individuals with obesity compared to running on a treadmill.

The current study investigated the feasibility of HFFS exercise at moderate-high intensities. Our results indicated that this exercise modality elicited comparable cardiovascular and metabolic responses (albeit a slightly lower Vo_2 relative to heart rate) to typical treadmill exercise across a single session, while also limiting peak tibial accelerations. The next logical step would be to determine if regular HFFS exercise can elicit the same general cardiovascular and cardiometabolic benefits as intensity matched walking and/or running exercise (i.e., weight loss, blood pressure reduction, etc.). Moreover, it would also be important to know if this HFFS modality could elicit these improvements while also maintaining a lower risk of joint pain. To answer this question, future studies may consider evaluating the long-term efficacy of HFFS for improving cardiometabolic health in individuals living with obesity or osteoarthritis. Long term studies of HHFS should also provide further information regarding the HR and VO_2 relationship differences noted in the current data. Finally, the effects of HFFS exercise in other clinical populations that might have reduced function which affects the ability to run, and the application in sports training should be explored and investigated.

Conclusion

Regular exercise of moderate-high intensity is a well-established guideline for the prevention and complementary treatment of several diseases. While running is a convenient and accessible exercise modality to meet this guideline, it also presents increased risk of injury in some clinical populations. The present study introduces a novel mode of treadmill exercise that uses a HFFS for exercise intensity monitoring and feedback on tibia axial accelerations. While HFFS exercise resulted in lower energy expenditure (< 1 MET) compared with treadmill walking/running for the same heart rate, it also involved a movement pattern that is associated with reduced tibia axial accelerations. Additionally, compared with independent treadmill walking/running, HFFS exercise was more accurate at meeting and maintaining target heart rates than independent exercise during the exercise session. Therefore, HFFS exercise is an alternative exercise modality for individuals with obesity that wish to participate in treadmill exercise and reduce knee injury risk.

Declarations

Funding

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Ethics approval

The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate

Informed consent and the University of Southern Mississippi IRB approval has been provided for human studies.

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Table 1

Table 1. Physiological parameters during baseline, and 40% HRR and 60% HRR exercise intensities. Non-steady state (NST) indicates measurements during the first four minutes of the exercise bout. Steady state (ST) indicates measurements during the last three minutes of the exercise bout.

		Baseline	40% HRR		60% HRR	
			NST	ST	NST	ST
HR target (bpm)	HFFS		124 ± 4.5		149 ± 3.9	
	IND		125 ± 3.9		149 ± 3.7	
HR (bpm)	HFFS	103 ± 13.6	120 ± 5.3	125 ± 4.7	141 ± 5.4	149 ± 4.5
	IND	103 ± 12.5	120 ± 7.8	127 ± 5.0	140 ± 5.9	151 ± 3.8
HRerr (bmp)	HFFS		6.9 ± 2.1 [a]	2.0 ± 0.8	11.6 ± 3.2 [a]	3.3 ± 2.0
	IND		9.1 ± 4.2 [a]	2.7 ± 2.0	13.4 ± 3.9 [a]	2.8 ± 1.5
VO2 (ml/kg/min)	HFFS	10.8 ± 1.7	15.2 ± 3.6	15.9 ± 3.8 [a]	19.2 ± 5.2 [a]	20.2 ± 5.8 [a]
	IND	11.0 ± 2.0	15.8 ± 3.3	17.2 ± 3.9 [a]	20.6 ± 5.2 [a]	22.8 ± 6.1 [a]
CHO (%)	HFFS	30.4 ± 17.0	42.5 ± 16.0	53.0 ± 16.9	55.8 ± 14.3	59.5 ± 11.2
	IND	31.9 ± 16.2	40.1 ± 14.1	48.3 ± 14.6	49.6 ± 14.7	56.8 ± 16.2
FAT (%)	HFFS	69.6 ± 17.0	57.9 ± 16.0	47.0 ± 16.0	44.2 ± 14.3	40.4 ± 11.2
	IND	68.0 ± 16.2	60.0 ± 14.9	51.7 ± 14.6	50.4 ± 14.7	43.2 ± 16.2

[a] indicates statistical differences between conditions

Figure 1

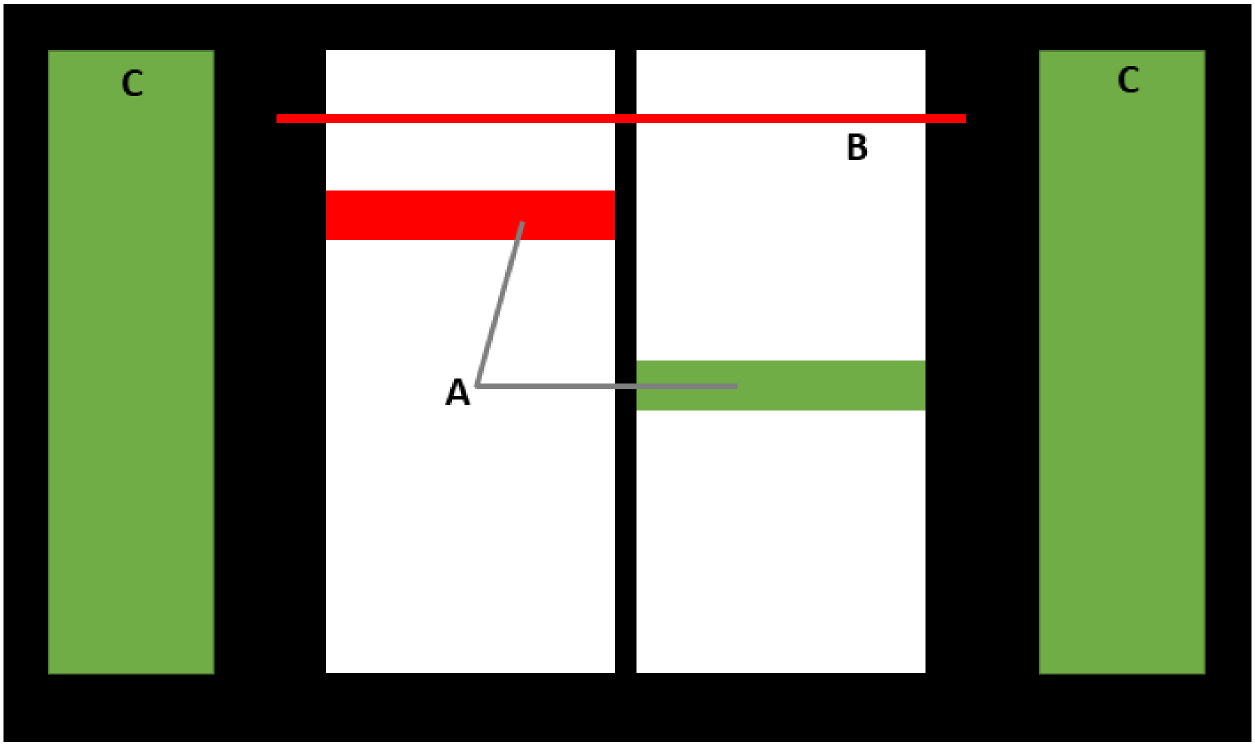

Figure 1. HFFS display during HFFS exercise. Right/Left hip flexion displays (A) indicate hip flexion during the exercise. During HFFS exercise, each indicator moves vertically according to the participant's hip flexion for each stride. Each hip flexion indicator also provides feedback on the tibia PPA. If the participant's stride results in PPA above the 3g threshold, the respective indicator will be red for that stride (A left). If the participant keeps PPA below the 3g threshold, the respective indicator will be green for that stride (A right). The red line (B) across both hip flexion displays is the target for maximum hip flexion. During the test, the line would move vertically, according to the target exercise intensity, indicating how much participants should flex their hips. Right/Left arm swing displays provided feedback on the amount of acceleration measured by the wrist IMUs. If the participants were accelerating their wrists below baseline walking levels, the displays would turn red.

Figure 2

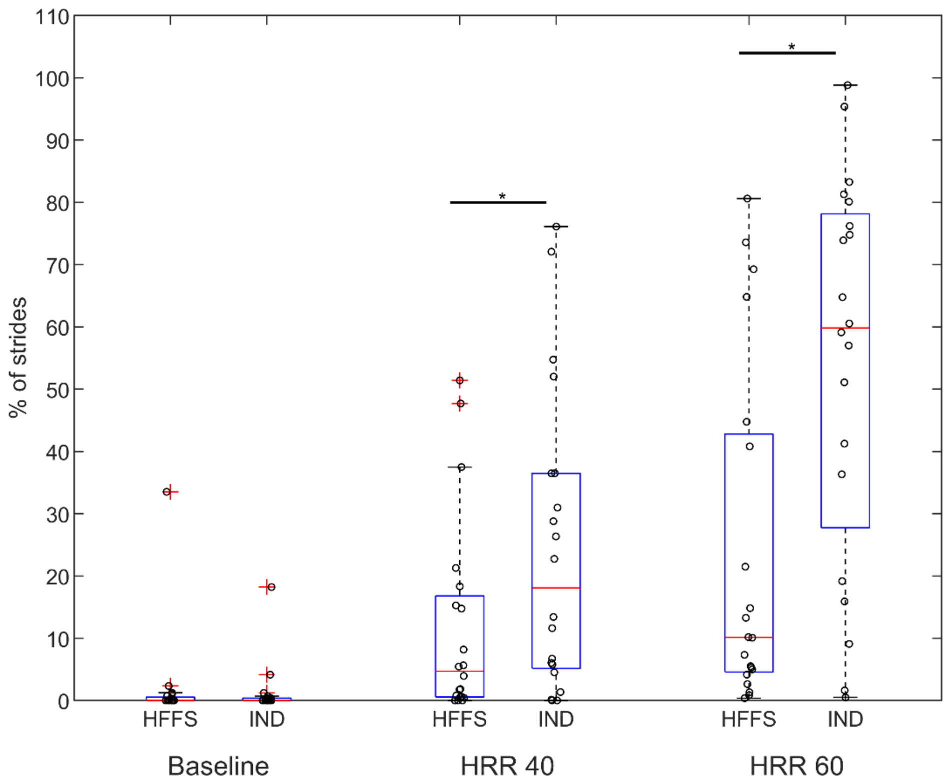

Figure 2. Percentage of strides during the exercise bouts with tibia PPA above 3g ($T_{PPA\%}$). Black open circles indicate individual participants. Whiskers indicate maximum and minimum values not considered outliers. Bottom and top edges of the blue box indicate the 25th and 75th percentiles. Central red line indicates the median. Red crosses indicate outliers. Outliers were included in the analysis for determining maximum and minimum whiskers and box limits. Black lines with * on top indicate statistical differences.

Figure 3

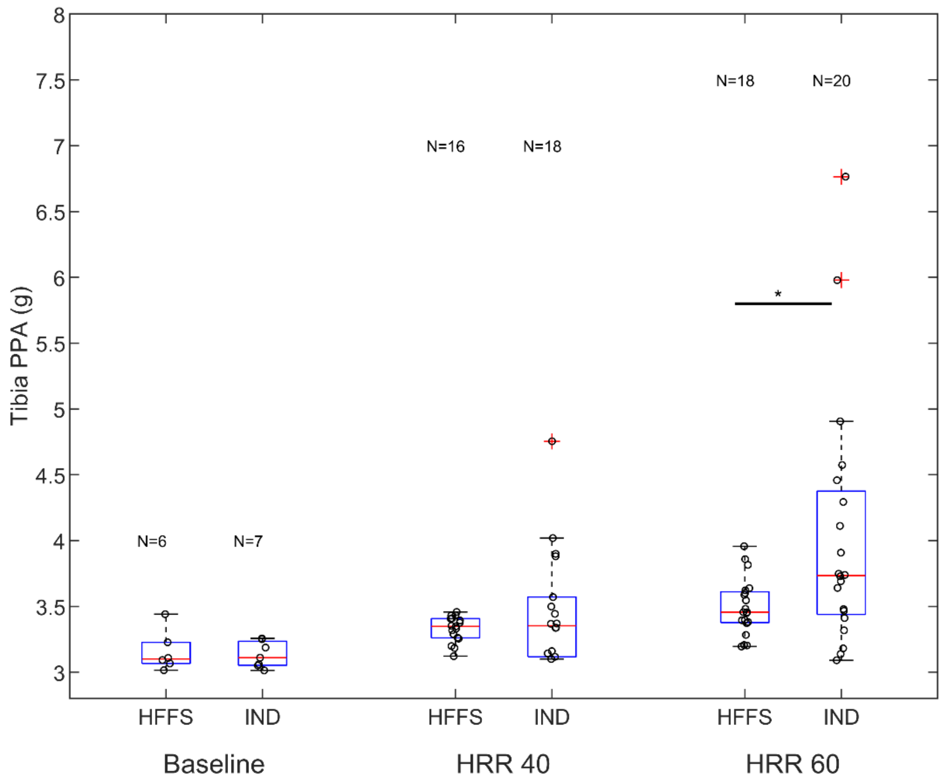

Figure 3. Mean tibia PPA including only strides that recorded PPA above the 3g threshold (T_{PPA}). Black open circles indicate individual participants. Whiskers indicate maximum and minimum values not considered outliers. Bottom and top edges of the blue box indicate the 25th and 75th percentiles. Central red line indicates the median. Red crosses indicate outliers. N indicates the number of participants included in the analysis (i.e., recorded tibia PPAs above 3g). Outliers were included in the analysis for determining maximum and minimum whiskers and box limits. Black line with * on top indicates statistical differences.