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Abstract

The ability to meet high exercise intensities is limited by the increased risk of injury in some clinical populations. Previous studies have linked large tibia peak positive accelerations resulting from running to increased risk of developing lower-extremity injury. The purpose of this study is to determine the feasibility of using a hip flexion feedback system (HFFS) to meet and maintain different exercise intensities while maintaining low tibia axial accelerations. Ten healthy participants were tested on a HFFS test and an independent walking/running test to meet exercise intensities of 40% and 60% of heart rate reserve (HRR). During the HFFS test, the HFFS controlled in real time the exercise intensity by directing individuals to specific maximum hip flexion targets during walking and providing visual information that assists them in maintaining low tibia peak positive accelerations during the initial contact phase. Maximum hip flexion targets during walking are calculated based on real-time readings of the participant's heart rate. During the independent test, exercise intensity was controlled independently by the participant using treadmill speed. Compared to the independent test, using the HFFS at 60% HRR resulted in similar heart-rate error but lower tibia peak positive accelerations. No differences were observed for the 40% HRR intensity. This paper describes a novel exercise approach that uses the individual's heart rate to calculate maximal hip flexion targets that an individual should meet during treadmill walking. The HFFS also provides tibia peak positive peak acceleration cues. Therefore, the HFFS can increase and control exercise intensities while maintaining low tibia accelerations. In particular, the HFFS might be an alternative strategy to meet moderate to vigorous exercise intensities in populations at risk of developing lower-extremity injuries.

Keywords

Biofeedback, exercise intensity controller, tibia peak accelerations, inertial measurement units, heart rate.

1. Introduction

Exercise offers numerous health benefits but can also present some risks for specific populations (1). The American College of Sports Medicine (ACSM) guidelines for exercise prescription indicate specific exercise parameters (frequency, intensity, time, and type of exercise) for designing exercise programs (1). However, the correct implementation of these guidelines can be difficult for two reasons: 1) concepts such as %VO_2 reserve (%VO_2R) or heart rate reserve (HRR) might be difficult to interpret and apply independently by individuals not familiar with exercise prescription, and 2) they do not address specific exercise limitations. In particular, the effort to meet moderate to vigorous intensity levels of exercise has the potential to lead to activities that involve high tibia peak positive accelerations (PPA), which have been associated with increased risk of osteoarthritis and stress fractures in some populations (2–5). For example, when exercising independently on a treadmill, participants increase exercise intensity by increasing treadmill speed, leading to jogging or running, which results in higher tibia PPAs than walking. Although walking and low-intensity jogging are associated with low risk of injury (6)(7), these low-intensity exercise dosages limit the possibility of meeting ACSM guidelines for high-intensity exercise, and consequently, prevent optimal cardiovascular and functional benefits, or clinically meaningful weight loss. In addition, ACSM guidelines do not specify exercise plans nor provide comprehensive detail for how to execute activities to reach specific intensity goals. For example, guidelines do not include alternative strategies to meet exercise recommendations for individuals with knee osteoarthritis or at risk of tibia stress fractures. Therefore, alternative methods that can monitor and elevate exercise intensity while performing activities appropriate for individuals at risk of musculoskeletal injury should be investigated.

Biofeedback is a technique that provides the individual with real-time information about specific parameters during movement. It has been shown to assist individuals in modifying movements to meet specific task goals (8,9) or targeting gait deviations (10,11). Additionally, introducing gait deviations has been shown to increase metabolic cost (12–14). Therefore, biofeedback might be a technique used to meet moderate to vigorous intensity levels of exercise by introducing specific gait deviations during comfortable walking speeds.

The purpose of this study is to introduce and investigate the feasibility of a visual biofeedback system, the hip flexion feedback system (HFFS), to monitor and control exercise intensities. During treadmill walking at comfortable speeds, the HFFS uses the individual's heart rate to calculate maximal hip flexion targets to meet specific exercise intensities. The HFFS also provides the user with feedback on tibia PPA to help maintain low tibia PPA during initial contact (15) (16). Therefore, exercise intensity and metabolic cost is increased by increasing hip flexion during walking, and actively controlling the dropping of the foot for initial contact during the terminal swing phase of the cycle (15). In this paper, the principles of operation and a feasibility study to assess the ability of healthy individuals to meet specific exercise intensities using the HFFS are shared.

2. Methods

2.1 Participants

Ten healthy participants (5M, 5F; age: 24.7 ± 4.9 years; height: 172 ± 10 cm; body mass: 68.7 ± 10.7 Kg) participated in this study. 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 feedback software was developed using MATLAB (The Mathworks, Natick, MA) and the MTW Devkit (Xsens Technologies BV, Enschede, Netherlands) programming interface. Seven inertial measurement units (IMUs) (Xsens) were placed on the lower limbs and wrists (sacrum, left and right anterior thigh, left and right distal tibia, and left/right wrists). A sensor-based measurement of the hip flexion angle was calculated as the difference between the thigh and sacrum sensors' rotation about the sensor's longitudinal axis ('roll axis') (10). A sampling rate of 100 Hz was used for orientation and acceleration data. Calibration procedures as described below were used to process the raw sensor-based angle for feedback generation. Acceleration data were low-pass filtered at a cut-off frequency of 30 Hz (9,17). A Polar H7 chest strap monitor (Polar Electro Oy, Kempele, Finland) was used to measure heart rate. The HRR was calculated as the difference between the estimated maximal heart rate and the resting heart rate. Resting heart rate was measured using the heart rate monitor after at least four minutes of seated rest at the beginning of the visit. Maximal heart rate was estimated using the 220-age formula (18). Tibia PPA were calculated using an IMU (Xsens Technologies BV, Enschede, Netherlands) aligned in the long axis of the participant's tibia attached to anteromedial aspect of the distal tibia using double-sided adhesive tape (German Brown, Walker Tape, UT, USA) and a Velcro strip (9,16,19). During HFFS exercise, tibia PPA were determined as the maximum value measured during the extension phase of the hip. Hip extension phase was determined as the period between maximum hip flexion and minimum hip flexion. This period included the mid/terminal swing phase and initial contact phase of the gait cycle (15). The maximum value measured during the extension phase of the hip was used because it was observed during HFFS exercise a large variability of rear and forefoot contact patterns that were different from typically reported PPA curves for walking/running. This limited the ability to detect foot initial contact. A 3g threshold was set to maintain participants closer to typical walking PPA values and below typical jogging/running values while using the HFFS (17,20). If participants performed a stride with PPA above the threshold, the respective indicator on the display would change from green to red.

During treadmill walking, a screen placed in front of the treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) displayed information with 1) the maximum hip flexion for each stride, 2) the target for maximum hip flexion, 3) the tibia PPA, and 4) the arm swing linear accelerations (Fig. 1). The maximum hip flexion for each stride was determined by calculating the maximum value in a 116-sample moving window. The HFFS calculated the target for maximum hip flexion using a Proportional-Integral-Derivative (PID) control loop mechanism (21) that uses the target heart rate and actual heart rate as input parameters (Fig. 2). Feedback on arm swing linear accelerations was given to promote arm movement. During preliminary testing, it was observed that some participants were 'freezing' their arms and focusing exclusively on meeting the hip flexion targets. Therefore, participants were asked to maintain the arm swing indicators to be green by moving their wrists at a minimum linear acceleration corresponding to their normal walking values.

**** Figure 1 here****

**** Figure 2 here****

2.3 Experimental Procedures

To investigate the feasibility of the HFFS at 40% HRR and 60% HRR exercise intensities (1), a repeated measures design with an intervention (HHFS test) and control condition (independent test) was used. During the intervention, participants used the HFFS to meet 40% HRR and 60% HRR exercise intensities. The control condition represented a standard treadmill exercise session where participants meet exercise intensities by controlling the treadmill speed. Differences in heart rate error and tibia PPA (M_{PPA}) were investigated. Difference in heart rate error during the whole trial (0 - 6 minutes) (HR_{err}), during the first two minutes of the trial ($HR2_{err}$), and during the last four minutes of the trial ($HR4_{err}$) were monitored to investigate the progression of heart rate error during the trial.

Testing commenced with familiarization to walking on the treadmill while selecting a preferred walking speed (PWS) which was used for all HFFS testing. A static calibration step was used to determine the zero position for hip flexion. A dynamic calibration step that involved walking on the treadmill for 10 seconds at PWS with maximal hip flexion was used to determine the maximum hip flexion at PWS for each participant. During dynamic calibration, participants were asked to walk on the treadmill with their maximum hip flexion ('lifting their knees as much as possible'). This step was used to set the upper limit for the hip flexion target display during HFFS training.

To determine their baseline heart rate at PWS, participants walked on the treadmill at PWS for 6 minutes. Baseline heart rate at PWS was used to represent the expected increase in heart rate resulting from standard walking on the treadmill at PWS alone (without the HFFS). 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 try the device until the association between the feedback cues and the corresponding movement features was sufficiently clear. Two exercise trials using the HFFS (HFFS) and two independent (IND) exercise trials, in random order, followed. The HFFS trials consisted of 6-minute bouts where participants used the HFFS to meet 40% HRR and 60% HRR exercise intensities. The IND trials consisted of 6-minute standard treadmill walking and running exercise where participants were able to control the treadmill speed to meet a specific heart rate corresponding to 40% and 60% HRR. During the IND trials, participants were able to see the target heart rate and their current heart rate. Participants rested 6 minutes between trials. Target heart rates were calculated to meet specific percentages of heart rate reserve.

Feedback Error (FE) was calculated as the mean across the trial of the absolute errors between the target maximum hip flexion and the actual maximum hip flexion. FE was expressed as a percentage of the maximum hip flexion (i.e., maximum possible observed error). Heart rate error (HR_{err}) was calculated as the absolute error between the target heart rate and the actual heart rate. The mean peak positive acceleration (M_{PPA}) was calculated as the mean tibia PPA across all recorded strides for both sides for each trial.

2.4 Statistical Analysis

Paired sample t-tests were used to test for significant differences in HR_{err} and M_{PPA} between the HFFS intervention and the standard treadmill exercise. The assumption of normality of distribution was tested by examining skew and kurtosis levels. Cohen’s d (d) was used to estimate effect sizes. A significance level of 0.05 was used for all statistical testing. Descriptive statistics (mean ± standard deviation) were calculated for each measure.

3. Results

The 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%).

No statistically significant differences between the HFFS trials (40% HRR: 8.1 ± 2.4 bpm; 60% HRR: 17.6 ± 8.8 bpm) and the respective IND trials (40% HRR: 6.7 ± 1.7 bpm; 60% HRR: 12.9 ± 3.6 bpm) were observed for the mean HR_{err} (HFFS 40% vs IND 40%: $t(9) = 1.61$, $p = 0.141$, $d = 0.5$; HFFS 60% vs IND 60%: $t(9) = 2.10$, $p = 0.065$, $d = 0.6$). Significant differences between the HFFS trials (40% HRR: 17.0 ± 4.0 bpm; 60% HRR: 28.9 ± 8.6 bpm) and the respective IND trials (40% HRR: 12.5 ± 4.1 bpm; 60% HRR: 30.5 ± 8.9 bpm) were observed for $HR2_{err}$ during the 40% HRR trial ($t(9) = 3.75$, $p = 0.031$, $d = 0.8$). No differences were observed for $HR2_{err}$ during the 60% HRR trial ($t(9) = -0.77$, $p = 0.463$, $d = 0.2$). Significant differences between the HFFS trials (40% HRR: 3.7 ± 1.9 bpm; 60% HRR: 12.0 ± 9.4 bpm) and the respective IND trials (40% HRR: 3.8 ± 2.0 bpm; 60% HRR: 4.1 ± 2.4 bpm) were observed for $HR4_{err}$ during the 60% HRR trial ($t(9) = 2.54$, $p = 0.005$, $d = 1.2$). No differences were observed for $HR4_{err}$ during the 40% HRR trial ($t(9) = -0.18$, $p = 0.862$, $d = 0.1$). Mean HR_{err} across the trial for the baseline trials was 33.5 ± 10.6 bpm for 40% HRR and 54.0 ± 6.2 bpm for 60% HRR.

HFFS M_{PPA} at 60% HRR was significantly smaller than IND M_{PPA} at 60% HRR ($t(19) = -4.46$, $p < 0.01$, $d = 1.0$). No differences were observed between HFFS and IND at 40% HRR ($t(19) = -0.56$, $p = 0.58$, $d = -0.1$) (Fig. 3).

**** Figure 3 here****

4. Discussion

A novel approach to exercise that uses a hip flexion feedback system controlled by the individual's heart rate to meet and maintain specific exercise intensities is reported. This approach aims to facilitate meeting specific exercise intensities while maintaining low tibia PPA during treadmill walking.

Low FE indicates that participants were able to follow the maximum hip flexion targets. Participants reported an average maximum hip flexion of 102° during PWS. This value corresponds to approximately 6.9° of error between the target and the actual maximum hip flexion during the trials. This error might be due to the difficulty in translating the error observed in the display to the actual movement requirements, particularly when large movement changes were required. Additionally, for 60% HRR trials, the target would require some participants to maintain relatively prolonged periods of maximum hip flexion. During these periods, local muscular fatigue might have prevented participants from maintaining levels of maximum hip flexion.

**** Figure 4 here ****

HFFS was able to control a participant's exercise intensity by increasing and decreasing maximum hip flexion during treadmill walking. Trials using the HFFS resulted in HR_{err} similar to trials where the exercise intensity was controlled by participants independently (IND). However, differences between the two approaches in the progression of HR_{err} during the 6-minute trials were observed. Figure 4 illustrates the mean HR_{err} during the trial across all participants. For the 40% HRR intensity, IND resulted in an initial (0 – 2 min.) quicker reduction of HRerr compared with the HFFS but with both systems maintaining similar levels of error during the rest of the trial (4 – 6 min.). For the 60% HRR intensity, the HFFS and IND were similar at reducing HR_{err} during the initial period of the trial (0 – 2 min.) but resulted in slightly larger errors and variability during the rest of the trial. The differences in heart rate error observed between exercise intensities might be explained by the different treadmill speed ranges required for each intensity. The 40% HRR usually required a treadmill speed that could be met with walking, which was easier for participants to assess and meet. The 60% HRR usually required a transition to jogging or running, which required treadmill speeds that might not be as familiar to the participants. Additionally, the HFFS uses a PID controller that adjusts the maximum hip flexion target based on a control loop employing error feedback between the target heart rate and the actual heart rate. At the beginning of the trial, this error was larger for the 60% HRR than the 40 % HRR condition. The HFFS had a quicker and steeper response to this error than the participants during the independent trial (IND). The HFFS produced this response by providing the user with maximal and submaximal targets for maximum hip flexion at the onset of the 60% HRR trials. Finally, the increased variability in the HFFS might be explained by the PID controller mechanism that allowed for larger errors above the target heart rate compared to IND. The PID controller is limited to three input parameters that are used in the computation of the maximum hip flexion feedback target. In this study, the parameters were maintained constant across participants, thus not accounting for individual variations in heart rate responses. Additionally, the control parameters were determined based on a small sample size, which limits their application across different individuals.

Overall, the M_{PPA} values reported while using the HFFS are below the threshold set by the HFFS. In particular, the current study demonstrated that participants exercising with the HFFS at 60% HRR had lower tibia PPA than exercising independently (IND) at the same intensity. This difference might be due to the different activities required to meet the specific exercise intensities. During the testing, it was observed that while most participants were able to meet the target heart rate by using a range of treadmill speeds that allowed for walking during the 40% HRR trials, all participants transitioned to jogging or running during the 60% HRR trials. The average value across participants observed for IND at 60% was 4.1g, which is within the range of previous values reported for jogging (17) and is below previously reported values for running (16,17). Therefore, the HFFS allowed participants to exercise at 60% HRR intensities while maintaining PPA below jogging and running values. This observation might be particularly important for clinical populations that benefit from moderate- to high-intensity exercise but cannot tolerate high tibia PPA, such as osteoarthritis (22)(23)(24) or older adults (25)(26), or that typically report higher tibia PPA and ground reaction forces compared to their healthy matched participants (3)(9).

5. Conclusions

The HFFS introduces a new approach to exercise that increases intensity and metabolic cost by directing participants to specific maximum hip flexion targets and lower tibia PPA during walking. This approach results in treadmill walking with increased hip flexion and active control of dropping the foot during the terminal swing phase to reduce initial contact accelerations. Therefore, the HFFS allows individuals to meet and maintain moderate to vigorous exercise intensities with tibia axial accelerations equivalent to comfortable walking. Additionally, the HFFS controller adjusts, in real-time, the peak hip flexion targets during treadmill walking to maintain the participant at the desired intensity level. The HFFS might be a particularly effective exercise modality for meeting moderate to vigorous intensities in clinical populations that benefit from moderate- to high-intensity treadmill exercise but are constrained by high tibia PPA.

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Figure Captions

Figure 1. HFFS display showed during treadmill walking. Right/Left hip flexion displays (A, center) indicate the maximum hip flexion during the exercise. Each indicator moves vertically according to the participant's maximum 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 threshold, the respective indicator will be red for that stride. The red line across both hip flexion displays (B) 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. Illustration of the setup, and flowchart of the process to calculate the maximum hip flexion targets based of the participants heart rate and target heart rate.

Figure 3. M_{PPA} for baseline, and during exercising at 40% HRR and 60% HRR with the HFFS (dashed line) and independently (IND) (solid line). Error bars denote group standard errors. * indicates statistical significant differences between HFFS and IND ($p \leq 0.05$).

Figure 4. HR_{err} progression during baseline (black), HFFS (green), and IND (red) across all participants. Solid line indicates the mean across participants and the shaded area indicates the standard error.