

4-29-2022

Feasibility of a Hip Flexion Feedback System For Controlling Exercise Intensity and Tibia Axial Peak Accelerations During Treadmill Walking

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Recommended Citation

Oliveira, N., Chiu, C. (2022). Feasibility of a Hip Flexion Feedback System For Controlling Exercise Intensity and Tibia Axial Peak Accelerations During Treadmill Walking. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*. Available at: https://aquila.usm.edu/fac_pubs/19988

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1 **Feasibility of a hip flexion feedback system for controlling exercise intensity and tibia axial peak**
2 **accelerations during treadmill walking**

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4

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19 **Acknowledgments**

20 This study was supported by the National Institute of General Medical Sciences of the National

21 Institutes of Health [grant number U54GM115428 NIH] and the University of Southern Mississippi.

22 No other conflict of interests to declare.

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27

28 Abstract

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

48

49 Keywords

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

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55 **1. Introduction**

56 Exercise offers numerous health benefits but can also present some risks for specific populations
57 (1). The American College of Sports Medicine (ACSM) guidelines for exercise prescription indicate
58 specific exercise parameters (frequency, intensity, time, and type of exercise) for designing exercise
59 programs (1). However, the correct implementation of these guidelines can be difficult for two
60 reasons: 1) concepts such as %VO₂ reserve (%VO₂R) or heart rate reserve (HRR) might be difficult to
61 interpret and apply independently by individuals not familiar with exercise prescription, and 2) they
62 do not address specific exercise limitations. In particular, the effort to meet moderate to vigorous
63 intensity levels of exercise has the potential to lead to activities that involve high tibia peak positive
64 accelerations (PPA), which have been associated with increased risk of osteoarthritis and stress
65 fractures in some populations (2–5). For example, when exercising independently on a treadmill,
66 participants increase exercise intensity by increasing treadmill speed, leading to jogging or running,
67 which results in higher tibia PPAs than walking. Although walking and low-intensity jogging are
68 associated with low risk of injury (6)(7), these low-intensity exercise dosages limit the possibility of
69 meeting ACSM guidelines for high-intensity exercise, and consequently, prevent optimal
70 cardiovascular and functional benefits, or clinically meaningful weight loss. In addition, ACSM
71 guidelines do not specify exercise plans nor provide comprehensive detail for how to execute
72 activities to reach specific intensity goals. For example, guidelines do not include alternative
73 strategies to meet exercise recommendations for individuals with knee osteoarthritis or at risk of tibia
74 stress fractures. Therefore, alternative methods that can monitor and elevate exercise intensity while
75 performing activities appropriate for individuals at risk of musculoskeletal injury should be
76 investigated.

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

82 comfortable walking speeds.

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

92

93 **2. Methods**

94 *2.1 Participants*

95 Ten healthy participants (5M, 5F; age: 24.7 ± 4.9 years; height: 172 ± 10 cm; body mass: $68.7 \pm$
96 10.7 Kg) participated in this study. This study was approved by the University of Southern Mississippi
97 Institutional Review Board. Participants were informed of the benefits and risks of the investigation
98 before providing written consent.

99

100 *2.2 The Hip Flexion Feedback System*

101 The feedback software was developed using MATLAB (The Mathworks, Natick, MA) and the
102 MTW Devkit (Xsens Technologies BV, Enschede, Netherlands) programming interface. Seven inertial
103 measurement units (IMUs) (Xsens) were placed on the lower limbs and wrists (sacrum, left and right
104 anterior thigh, left and right distal tibia, and left/right wrists). A sensor-based measurement of the hip

105 flexion angle was calculated as the difference between the thigh and sacrum sensors' rotation about the
106 sensor's longitudinal axis ('roll axis') (10). A sampling rate of 100 Hz was used for orientation and
107 acceleration data. Calibration procedures as described below were used to process the raw sensor-based
108 angle for feedback generation. Acceleration data were low-pass filtered at a cut-off frequency of 30 Hz
109 (9,17). A Polar H7 chest strap monitor (Polar Electro Oy, Kempele, Finland) was used to measure heart
110 rate. The HRR was calculated as the difference between the estimated maximal heart rate and the resting
111 heart rate. Resting heart rate was measured using the heart rate monitor after at least four minutes of
112 seated rest at the beginning of the visit. Maximal heart rate was estimated using the 220-age formula
113 (18). Tibia PPA were calculated using an IMU (Xsens Technologies BV, Enschede, Netherlands)
114 aligned in the long axis of the participant's tibia attached to anteromedial aspect of the distal tibia using
115 double-sided adhesive tape (German Brown, Walker Tape, UT, USA) and a Velcro strip (9,16,19).
116 During HFFS exercise, tibia PPA were determined as the maximum value measured during the
117 extension phase of the hip. Hip extension phase was determined as the period between maximum hip
118 flexion and minimum hip flexion. This period included the mid/terminal swing phase and initial contact
119 phase of the gait cycle (15). The maximum value measured during the extension phase of the hip was
120 used because it was observed during HFFS exercise a large variability of rear and forefoot contact
121 patterns that were different from typically reported PPA curves for walking/running. This limited the
122 ability to detect foot initial contact. A 3g threshold was set to maintain participants closer to typical
123 walking PPA values and below typical jogging/running values while using the HFFS (17,20). If
124 participants performed a stride with PPA above the threshold, the respective indicator on the display
125 would change from green to red.

126 During treadmill walking, a screen placed in front of the treadmill (Force-sensing tandem treadmill,
127 AMTI, Watertown, MA, USA) displayed information with 1) the maximum hip flexion for each stride,
128 2) the target for maximum hip flexion, 3) the tibia PPA, and 4) the arm swing linear accelerations (Fig.
129 1). The maximum hip flexion for each stride was determined by calculating the maximum value in a
130 116-sample moving window. The HFFS calculated the target for maximum hip flexion using a
131 Proportional-Integral-Derivative (PID) control loop mechanism (21) that uses the target heart rate and

132 actual heart rate as input parameters (Fig. 2). Feedback on arm swing linear accelerations was given to
133 promote arm movement. During preliminary testing, it was observed that some participants were
134 ‘freezing’ their arms and focusing exclusively on meeting the hip flexion targets. Therefore, participants
135 were asked to maintain the arm swing indicators to be green by moving their wrists at a minimum linear
136 acceleration corresponding to their normal walking values.

137

138 **** Figure 1 here****

139

140 **** Figure 2 here****

141

142 2.3 Experimental Procedures

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

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

158 To determine their baseline heart rate at PWS, participants walked on the treadmill at PWS for 6
159 minutes. Baseline heart rate at PWS was used to represent the expected increase in heart rate resulting
160 from standard walking on the treadmill at PWS alone (without the HFFS). The feedback interface was
161 then introduced and explained. Participants were introduced to the visual display and were told what
162 movement related information was being given by each indicator. After this introduction, participants
163 were allowed to try the device until the association between the feedback cues and the corresponding
164 movement features was sufficiently clear. Two exercise trials using the HFFS (HFFS) and two
165 independent (IND) exercise trials, in random order, followed. The HFFS trials consisted of 6-minute
166 bouts where participants used the HFFS to meet 40% HRR and 60% HRR exercise intensities. The IND
167 trials consisted of 6-minute standard treadmill walking and running exercise where participants were
168 able to control the treadmill speed to meet a specific heart rate corresponding to 40% and 60% HRR.
169 During the IND trials, participants were able to see the target heart rate and their current heart rate.
170 Participants rested 6 minutes between trials. Target heart rates were calculated to meet specific
171 percentages of heart rate reserve.

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

178

179 *2.4 Statistical Analysis*

180 Paired sample t-tests were used to test for significant differences in HR_{err} and M_{PPA} between the
181 HFFS intervention and the standard treadmill exercise. The assumption of normality of distribution
182 was tested by examining skew and kurtosis levels. Cohen's d (d) was used to estimate effect sizes. A

183 significance level of 0.05 was used for all statistical testing. Descriptive statistics (mean \pm standard
184 deviation) were calculated for each measure.

185 3. Results

186 The FE across sides and intensities was below 10% (right side at 40% HRR: $6.9 \pm 4.5\%$;
187 left side at 40% HRR: $7.0 \pm 3.7\%$; right side at 60% HRR: $7.3 \pm 5.5\%$; left side at 60% HRR:
188 $7.3 \pm 5.3\%$).

189 No statistically significant differences between the HFFS trials (40% HRR: 8.1 ± 2.4 bpm; 60%
190 HRR: 17.6 ± 8.8 bpm) and the respective IND trials (40% HRR: 6.7 ± 1.7 bpm; 60% HRR: 12.9 ± 3.6
191 bpm) were observed for the mean HR_{err} (HFFS 40% vs IND 40%: $t(9) = 1.61$, $p = 0.141$, $d = 0.5$;
192 HFFS 60% vs IND 60%: $t(9) = 2.10$, $p = 0.065$, $d = 0.6$). Significant differences between the HFFS
193 trials (40% HRR: 17.0 ± 4.0 bpm; 60% HRR: 28.9 ± 8.6 bpm) and the respective IND trials (40%
194 HRR: 12.5 ± 4.1 bpm; 60% HRR: 30.5 ± 8.9 bpm) were observed for HR_{2err} during the 40% HRR
195 trial ($t(9) = 3.75$, $p = 0.031$, $d = 0.8$). No differences were observed for HR_{2err} during the 60% HRR
196 trial ($t(9) = -0.77$, $p = 0.463$, $d = 0.2$). Significant differences between the HFFS trials (40% HRR:
197 3.7 ± 1.9 bpm; 60% HRR: 12.0 ± 9.4 bpm) and the respective IND trials (40% HRR: 3.8 ± 2.0 bpm;
198 60% HRR: 4.1 ± 2.4 bpm) were observed for HR_{4err} during the 60% HRR trial ($t(9) = 2.54$, $p =$
199 0.005 , $d = 1.2$). No differences were observed for HR_{4err} during the 40% HRR trial ($t(9) = -0.18$, $p =$
200 0.862 , $d = 0.1$). Mean HR_{err} across the trial for the baseline trials was 33.5 ± 10.6 bpm for 40% HRR
201 and 54.0 ± 6.2 bpm for 60% HRR.

202 HFFS M_{PPA} at 60% HRR was significantly smaller than IND M_{PPA} at 60% HRR ($t(19) = -4.46$, p
203 < 0.01 , $d = 1.0$). No differences were observed between HFFS and IND at 40% HRR ($t(19) = -0.56$, p
204 $= 0.58$, $d = -0.1$) (Fig. 3).

205

206 **** Figure 3 here****

207

208 **4. Discussion**

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

212 Low FE indicates that participants were able to follow the maximum hip flexion targets. Participants
213 reported an average maximum hip flexion of 102° during PWS. This value corresponds to
214 approximately 6.9° of error between the target and the actual maximum hip flexion during the trials.
215 This error might be due to the difficulty in translating the error observed in the display to the actual
216 movement requirements, particularly when large movement changes were required. Additionally, for
217 60% HRR trials, the target would require some participants to maintain relatively prolonged periods of
218 maximum hip flexion. During these periods, local muscular fatigue might have prevented participants
219 from maintaining levels of maximum hip flexion.

220

221 **** Figure 4 here ****

222

223 HFFS was able to control a participant's exercise intensity by increasing and decreasing maximum
224 hip flexion during treadmill walking. Trials using the HFFS resulted in HR_{err} similar to trials where the
225 exercise intensity was controlled by participants independently (IND). However, differences between
226 the two approaches in the progression of HR_{err} during the 6-minute trials were observed. Figure 4
227 illustrates the mean HR_{err} during the trial across all participants. For the 40% HRR intensity, IND
228 resulted in an initial (0 – 2 min.) quicker reduction of HR_{err} compared with the HFFS but with both
229 systems maintaining similar levels of error during the rest of the trial (4 – 6 min.). For the 60% HRR
230 intensity, the HFFS and IND were similar at reducing HR_{err} during the initial period of the trial (0 – 2

231 min.) but resulted in slightly larger errors and variability during the rest of the trial. The differences in
232 heart rate error observed between exercise intensities might be explained by the different treadmill
233 speed ranges required for each intensity. The 40% HRR usually required a treadmill speed that could
234 be met with walking, which was easier for participants to assess and meet. The 60% HRR usually
235 required a transition to jogging or running, which required treadmill speeds that might not be as familiar
236 to the participants. Additionally, the HFFS uses a PID controller that adjusts the maximum hip flexion
237 target based on a control loop employing error feedback between the target heart rate and the actual
238 heart rate. At the beginning of the trial, this error was larger for the 60% HRR than the 40 % HRR
239 condition. The HFFS had a quicker and steeper response to this error than the participants during the
240 independent trial (IND). The HFFS produced this response by providing the user with maximal and
241 submaximal targets for maximum hip flexion at the onset of the 60% HRR trials. Finally, the increased
242 variability in the HFFS might be explained by the PID controller mechanism that allowed for larger
243 errors above the target heart rate compared to IND. The PID controller is limited to three input
244 parameters that are used in the computation of the maximum hip flexion feedback target. In this study,
245 the parameters were maintained constant across participants, thus not accounting for individual
246 variations in heart rate responses. Additionally, the control parameters were determined based on a
247 small sample size, which limits their application across different individuals.

248 Overall, the M_{PPA} values reported while using the HFFS are below the threshold set by the HFFS.
249 In particular, the current study demonstrated that participants exercising with the HFFS at 60% HRR
250 had lower tibia PPA than exercising independently (IND) at the same intensity. This difference might
251 be due to the different activities required to meet the specific exercise intensities. During the testing, it
252 was observed that while most participants were able to meet the target heart rate by using a range of
253 treadmill speeds that allowed for walking during the 40% HRR trials, all participants transitioned to
254 jogging or running during the 60% HRR trials. The average value across participants observed for IND
255 at 60% was 4.1g, which is within the range of previous values reported for jogging (17) and is below
256 previously reported values for running (16,17). Therefore, the HFFS allowed participants to exercise at
257 60% HRR intensities while maintaining PPA below jogging and running values. This observation might

258 be particularly important for clinical populations that benefit from moderate- to high-intensity exercise
259 but cannot tolerate high tibia PPA, such as osteoarthritis (22)(23)(24) or older adults (25)(26), or that
260 typically report higher tibia PPA and ground reaction forces compared to their healthy matched
261 participants (3)(9).

262

263 **5. Conclusions**

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

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368 *Figure Captions*

369

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

379

380 Figure 2. Illustration of the setup, and flowchart of the process to calculate the maximum hip flexion
381 targets based of the participants heart rate and target heart rate.

382

383

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

387

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

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