Plantar Pressure Variations During Exercise on Four Pieces of Commercially Available Cardiovascular Equipment

Amy G. Jorde[1,2], Shannon R. Ogren[1,3], Tanner R. Augustin[1,2], Tate A. Augustin[1,2], Gregory R. Bashford[2], and Judith M. Burnfield[1,2,3]

[1]Madonna Rehabilitation Hospital, Movement Sciences Center, Lincoln, NE, USA
[2]University of Nebraska – Lincoln, Lincoln, NE, USA
[3]University of Southern California, Los Angeles, CA, USA

Introduction

Cardiovascular exercise is a central component of national health efforts aimed at preventing chronic and secondary medical complications. While exercisers have a wide range of cardiovascular equipment to choose from, little has been published regarding the potential risks for foot injuries associated with various forms of exercise. Owing to the fact that prolonged and repetitive exposure to elevated plantar pressures can lead to pain and tissue injury in persons susceptible to orthopaedic and neuropathic foot disorders, a better understanding of the impact of different types of exercise on foot pressures appears warranted.[1,2]

Purpose

To explore plantar pressure variations during five cardiovascular exercises. These activities were selected due to expected variations in force distribution and contact area under the feet.

Hypotheses

- Peak foot pressures would be highest during exercises that include periods of supporting body weight on a single limb (i.e., running and walking) due to increased forces under the foot.
- Peak foot pressures would be lowest during recumbent exercise (i.e., biking) owing to reduced forces under the foot.

Methods

Subjects

5 males, 5 females with no known musculoskeletal or neurological disorders

Subject Characteristics (Mean ± SD)

Age (yrs)	Height (m)	Mass (kg)
23 ± 3	1.72 ± 0.09	75 ± 14

Instrumentation

Life Fitness™ Exercise Equipment

- Treadmill 97Ti (Figure 2A, B)
- Elliptical Cross-Trainer 95Xi (Figure 2C)
- Stairclimber 95Si (Figure 2D)
- Recumbent Bike 95Ri (Figure 2E)

Methods (cont.)

Instrumentation (cont.)

Pedar-X Dynamic pressure distribution system (novel electronics, inc.) recorded pressure variables (Figure 1).

- 14 pairs of insoles
- 99 capacitive sensors/insole
- 60 Hz sampling rate

Figure 1. Pedar pressure mapping system.

8 Camera Eagle Digital System (Motion Analysis Corporation) defined cyclical events for activities lacking periods of single limb support.

- 60 Hz sampling rate

Procedures

Sessions 1-3: Familiarization

Subjects familiarized with cardiovascular equipment and instructed to exercise at a speed that could be maintained for thirty minutes.

Session 4: Data Collection

- Subjects performed treadmill running, treadmill walking, elliptical training, stairclimbing, and recumbent biking (5 minutes each, order randomized, self-selected footwear).
- Plantar pressure variables and support surface kinematics recorded simultaneously during final minute of each exercise.

Data Analysis

Key plantar pressure variables in the heel, arch, and forefoot regions identified for the dominant limb (multimask software by novel electronics, inc):

- Mean Maximum Peak Pressure (PP)
- Mean Maximum Force (MF)
- Mean Contact Area (CA)

Statistical Analysis

- Separate one-way analyses of variance with repeated measures determined if PP, MF, or CA varied significantly across activities in each region.
- A Bonferroni adjusted alpha level of P<0.0167 assessed significance.

Results

Heel

Activity	PP (N/cm^2)	MF (N)	CA (cm^2)
Running (R)	19.4 ± 4.2	596 ± 140	46.5 ± 4.8
Walking (W)	22.6 ± 3.4	640 ± 120	46.4 ± 4.8
Elliptical Training (E)	9.9 ± 4.2	274 ± 158	40.0 ± 10.9
Stairclimbing (S)	7.6 ± 1.7	202 ± 70	39.0 ± 7.0
Recumbent Biking (B)	2.9 ± 1.1	34 ± 30	14.5 ± 11.5
Significant Main Effect	R,W > E,S >B (P ≤ 0.007)	R,W > E,S,B (P ≤ 0.001) S > B (P = 0.001)	R,W,E,S >B (P ≤ 0.003)

Arch

Activity	PP (N/cm^2)	MF (N)	CA (cm^2)
Running	15.1 ± 2.7	565 ± 149	63.1 ± 8.5
Walking	12.5 ± 1.6	256 ± 64	57.3 ± 9.9
Elliptical Training	11.1 ± 2.6	313 ± 93	57.6 ± 10.0
Stairclimbing	8.8 ± 2.2	263 ± 71	57.2 ± 8.9
Recumbent Biking	4.0 ± 1.2	70 ± 35	27.3 ± 12.0
Significant Main Effect	R > E,S > B (P < 0.009) W > S,B (P < 0.001)	R> W,E,S > B (P ≤ 0.001)	R > W > B (P ≤ 0.011) E,S > B (P ≤ 0.001)

Forefoot

Activity	PP (N/cm^2)	MF (N)	CA (cm^2)
Running	25.3 ± 4.5	1052 ± 202	81.2 ± 10.2
Walking	25.1 ± 7.6	820 ± 177	81.6 ± 9.9
Elliptical Training	18.8 ± 7.7	663 ± 302	76.2 ± 12.1
Stairclimbing	12.2 ± 4.2	438 ± 150	74.5 ± 14.5
Recumbent Biking	4.4 ± 1.3	105 ± 76	41.1 ± 24.9
Significant Main Effect	R,W > S,B (P ≤ 0.003) E,S > B (P ≤ 0.002)	R > W,E,S >B (P ≤ 0.003) W > S (P < 0.001)	R,W,E,S > B (P ≤ 0.005)

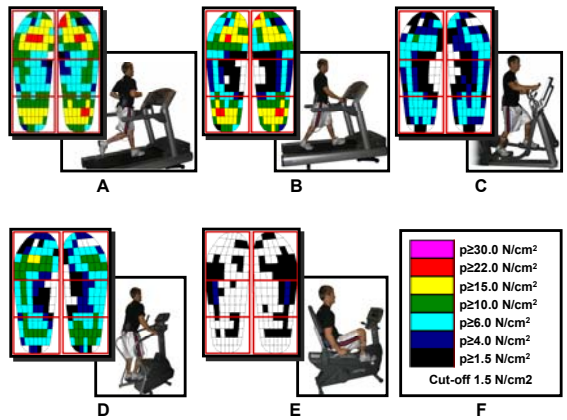

Figure 2. Exemplar subject performing each exercise and corresponding PP pressure map for: A) treadmill running; B) treadmill walking; C) elliptical training; D) stairclimbing; and E) recumbent biking. F) Legend for pressure maps. Note: Pressures depicted by pink and red colors could be potentially harmful for insensate feet.[1]

Discussion

Heel: Significantly higher PP occurred under the heel during walking and running compared to the other three conditions due to increases in MF as CA was not decreased. Despite a significant reduction in CA during biking, PP was significantly lower than all other conditions, owing to the decrease in MF.

Arch: PP was highest during running and lowest during biking in the arch region, consistent with the observed force pattern (i.e., highest MF during running, lowest MF during biking). This occurred despite the greatest CA being observed during running and the smallest CA being observed during biking. Walking PP was also significantly elevated compared to stairclimbing and biking. This arose from greater MF during walking compared to biking.

Forefoot: PP under the forefoot was significantly higher during running and walking compared to stairclimbing and biking owing to the increased MF during running and walking. PP was lowest during biking due to a significant reduction in MF and occurred despite the smaller CA while biking.

Summary

- Substantial pressure variations were documented among exercises, with PP varying greater than seven-fold under the heel, five-fold under the forefoot, and three-fold beneath the arch across activities. The primary cause of these differences was the change in maximum force when performing tasks, particularly those containing periods of single limb support compared to activities allowing double limb and buttock support.
- The findings from this study indicate that when protection of the heel from high pressures and forces is warranted, recumbent biking, stairclimbing and elliptical training provide greater relief compared to running and walking. When protection of the forefoot is of importance (e.g., with diabetic foot neuropathies), stairclimbing and biking appear to offer the optimal reduction in pressures.
- Further research is required involving persons with pathology.

References

[1]Mueller, M. et al. (1999). *Physical Therapy*, **79**(3), 296-307.
[2]Weist, R. et al. (2004). *American Journal of Sports* Medicine, **32**, 1893-1898.

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