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Comparison of plantar pressure profile of young adults during training on elliptical devices and overground walking: A pilot study

Guilherme Manna Cesar
Madonna Rehabilitation Hospitals, g.cesar@unf.edu

Thad W. Buster
Madonna Rehabilitation Hospitals, tbuster@madonna.org

Judith M. Burnfield
Madonna Rehabilitation Hospital, jburnfield@madonna.org

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Guilherme M. Cesar, Thad W. Buster, & Judith M. Burnfield

Institute for Rehabilitation Science and Engineering at Madonna Rehabilitation Hospitals, 5401 South Street, Lincoln, NE 68506, United States

Corresponding author — G.M. Cesar, *email* gcesar@madonna.org

Abstract

Background: Elliptical training may offer advantages over other cardiorespiratory exercises for those requiring podiatric care, since its constant double-limb support diminishes recurring high-impact plantar forces while allowing exercise in a functional, upright posture. Unknown is the impact of distinct elliptical models, that can alter user's body mechanics, on potential variations in plantar pressure patterns.

Purpose: To compare plantar pressure variables while exercising on four ellipticals and walking.

Methods: For this cross-sectional pilot study, plantar pressure data were recorded from ten young adults while exercising on four ellipticals (True, Octane, Life Fitness, SportsArt) and walking overground. One-way repeated measures ANOVA identified differences in heel, arch, and forefoot maximum force (MF), peak pressure (PP), and pressure-time integral (PTI).

Results: MF was lower under the heel when exercising on all ellipticals compared with walking, with further differences detected between models. PP was lower on all three foot regions when exercising on all ellipticals compared with walking,

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except Octane under the arch, with differences detected between ellipticals under the heel. PTI was lower under the heel and arch when exercising on some of the ellipticals compared with walking, with differences again detected under the heel between models.

Conclusion: Plantar pressures were lower when exercising on the ellipticals compared with walking for most variables. Caution is recommended to which elliptical could be incorporated into therapeutic programs given that differences among models were detected under the heel.

Keywords: Plantar pressure, Elliptical, Physical therapy, Exercise, Adults

1. Introduction

Foot disorders can make it difficult for some young adults to engage in exercises to address cardiorespiratory fitness, an important component of physical activity necessary for health and function. While ambulatory activities (e.g., walking, running) are used to achieve such goals, recurring exposure to elevated plantar impact forces has been associated with orthopedic conditions such as metatarsal stress fractures and subcalcaneal spurs [1–4]. Recurring walking/running plantar impact forces can also delay ongoing rehabilitation and aggravate existing podiatric disorders. The use of elliptical devices to strengthen lower extremity muscles and to improve cardiorespiratory fitness [5–7] has increased in popularity amongst the general population and rehabilitation professionals since ellipticals demonstrate an advantage over other modalities of cardiorespiratory training. Certain elliptical models can closely emulate the mechanics of gait without generating the repetitive high-impact plantar forces observed during overground or treadmill walking/running [3,8–12].

Design differences in commercial elliptical devices promote stride length and height that can vary considerably across models, with some devices further allowing for pedal excursion customization (e.g., horizontal trajectory) to the user's desired stride length [13]. The altered designs provide a diverse combination of lower extremity joint/segment positions throughout the elliptical movement cycle that impact user's body posture. In fact, a more flexed trunk position (9° to 10°) has been recorded while exercising on certain models (e.g. Life Fitness X7) compared with other elliptical models [9], potentially altering lower extremity loading mechanics. Collectively, these findings support the assumption that distinct pressure patterns could be experienced under key regions of the foot when exercising with different ellipticals.

Knowledge about plantar pressure variation across distinct elliptical models is crucial to provide safe elliptical exercise prescriptions for individuals prone to developing orthopedic podiatric conditions and for those undergoing podiatric rehabilitation. While previous work reported that peak forefoot pressure during elliptical training did not differ from those observed during treadmill jogging and walking, pressure variables under the heel were lower during elliptical training [10]. However, only one fixed-stride length elliptical model (i.e., Life Fitness) was utilized. Lacking to date is a study examining whether varying elliptical models influence plantar pressure differently in young adults.

The purpose of this preliminary study was to compare and quantify differences in young adults' plantar force and pressure profile while exercising on four elliptical devices and walking overground. The elliptical devices selected exhibited different mechanical features and we opted to investigate the designs' impact on individuals without known podiatric disorders or chronic conditions to establish a foundational work for future studies with patient populations. Since elliptical training provides constant double-limb support during its movement cycle, we hypothesized that (1) lower forces and thus reduced peak pressure would be observed during elliptical training compared with overground walking. Additionally, since floor/pedal contact time differs between elliptical training and walking, we also considered the time-dependent pressure between conditions. It is hypothesized that (2) the overall cumulative pressure within a movement cycle would be similar between elliptical training and walking since the reductions in peak pressure resulting from sustained double-limb support would be offset by the increased duration of pressure exposure.

2. Materials and methods

2.1. Participants

A convenience sampled group of 10 young adults, counterbalanced for sex (5 males and 5 females), participated in this cross-sectional study. Inclusion criteria involved no prior history of musculoskeletal, cardiovascular, or neurological injuries that would impact their capacity to exercise on an elliptical or to walk overground. Their mean age, height, and mass were 24.3 ± 4.7 years, 174.8 ± 7.5 cm, and 71.6 ± 12.6 kg, respectively. Nine participants were right limb dominant. Although not included as a criterion to participate, all participants had experience with using elliptical devices prior to engaging in the study. Additionally, all participants reported no musculoskeletal, neurological, or cardiovascular conditions that could impact their ability to walk or exercise on elliptical devices.

2.2. Materials

The Pedar® system (Novel Electronics Inc., Munich, Germany) was used to record the variables at 60 Hz using 2-mm-thick flexible insoles (calibrated per manufacturer's guidelines) inserted in the participants' shoes. A 10-m walkway was utilized for the walking trials. Data were extracted from the middle six meters of the walkway to reduce the effect of acceleration/deceleration on participants' plantar force and pressure variables.

Four elliptical models were selected based on the following criteria: They featured adjustable stride lengths (in contrast to models with fixed stride length) and, observationally, similar walking kinematics when individuals exercised on the devices. The only four elliptical models that met the criteria were (**Fig. 1**): Life Fitness X7 (Life Fitness Corporation, Schiller Park, IL) with stride length of 46–61 cm, Octane Fitness Pro 4500 (Octane Fitness, Brooklyn Park, MN) with stride length of 46–58 cm, SportsArt Fitness E870 (SportsArt Fitness, Woodinville, WA) with stride length of 43–74 cm, and True Fitness TSXa (TRUE Fitness Technology, St. Louis, MO) with stride length of 43–66 cm. While each device had stationary and moving handlebars, participants were directed to only use the moving handlebars.

2.3. Procedure

Informed consent procedures were followed to maintain individuals' safety, privacy, and rights. Individuals signed the written informed consent form approved by Madonna Rehabilitation Hospitals' Institutional Review Board. Each participant completed familiarization

Fig. 1. Elliptical models used in the current work from the manufacturers Life Fitness Corporation, Octane Fitness, SportsArt Fitness, and True Fitness Technology.

sessions before engaging in the study's data collection. Participants were asked to wear their habitual exercise clothes and shoes for these familiarization sessions. During these sessions, participants' anthropometrics and lower limb dominance were recorded. Following, participants traversed the walkway at a self-selected comfortable speed. Walking trials were performed until ten trials were completed at a speed of ± 5% of the average speed. Between 11 and 13 walking trials were needed to ensure ten comparable trials. After walking, participants were familiarized with each elliptical device in a random order. Elliptical stride length and speed were recorded for each participant as they simulated performing a typical exercise session at a self-selected pace. Participants were allowed to use the ellipticals for approximately three minutes with a 5-min rest period between devices.

Plantar pressure data collection was then scheduled within 24 h of the last familiarization session. Appropriate-sized insoles were placed inside the participants' shoes (between the insole and participants' foot) and a zero-pressure baseline was established for each insole by asking participants to lift their feet from the floor. Pedar force and pressure data were then recorded as participants engaged in the walking and elliptical trials using procedures similar to the familiarization session. Walking trials were performed prior to the elliptical trials since overground walking at self-selected pace was not expected to be fatiguing for young adults without known disabilities. For the elliptical trials, the order of elliptical devices used for training was randomized with a Matlab (MathWorks, Natick, MA, USA) script. All participants began exercising with the self-selected stride length and speed previously recorded from the familiarization session. Participants were allowed to adjust speed and stride length if they deemed it had changed from the familiarization session; however, none chose to do so. Once speed and stride length were confirmed, participants exercised for 2 min on each device. A 5-min rest interval was allowed between elliptical trials to minimize the impact of fatigue.

2.4. Data analysis

Data from walking trials were divided into steps with the software Emedlink (Novel Electronics, Inc., Munich, Germany). A walking cycle was defined as the period between the first stance phase pressure to the onset of the next stance phase pressure of the reference limb. For the elliptical trials, the same software defined the elliptical cycle as the window between successive pressure minima (typically occurring during upward pedal elevation) [10].

Foot masks were created from the data obtained from the pressure sensors and divided (Novel Multitask Evaluation software, Novel Electronics, Inc., Germany) into 3 anatomical regions (heel, arch, forefoot) using routines provided by the manufacturer (Percent Mask Insole-3).

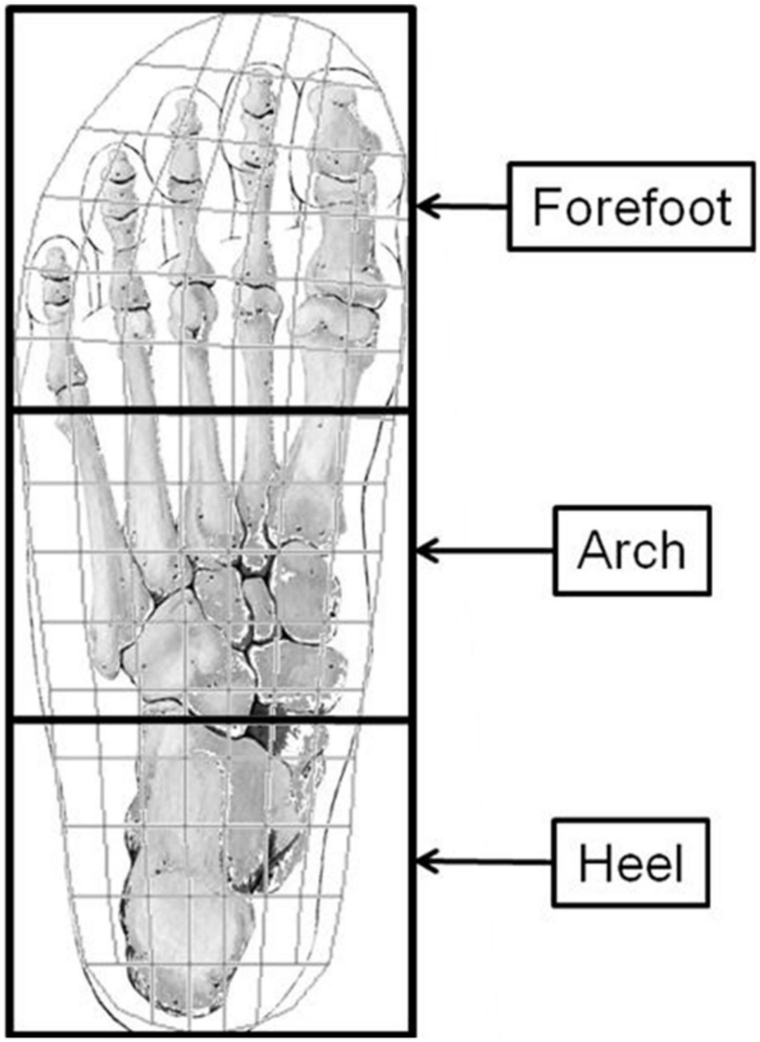

Fig. 2. Plantar view with the three masks used to define the anatomical regions of heel, arch, and forefoot.

Separate regional analyses of plantar force and pressure variables from the dominant limb were performed for each region, shown in **Fig. 2**: Heel (proximal 30% of longitudinal foot length), arch (intermediate 30% of longitudinal foot length), and forefoot (distal 40% of longitudinal foot length). Data used for statistical treatment were derived from the final minute of each condition.

Maximum force (MF), peak pressure (PP), and pressure-time integral (PTI) were calculated for all three regions for each walking and elliptical trial. MF (in N) was calculated by multiplying each individual pressure sensor in a given mask by the area of the sensor within the mask. PP was the absolute peak (in kPa) for each trial. PTI quantified the pressure experienced during a stride or cycle (in kPa*s).

2.5. Statistical analysis

Descriptive statistics were performed for all variables of interest. Next, assumptions of normality were assessed using the Shapiro–Wilk method. If normality assumptions passed, one-way analyses of variance (5 × 1 ANOVA) with repeated measures were used to identify if significant differences existed in the variables MF, PP, and PTI across conditions (i.e., 4 elliptical trainers and walking). Pairwise multiple comparisons were performed with the Holm-Sidak method to determine which conditions differed for each variable. If initial normality assumptions were violated, data were transformed into ranks and one-way ANOVA with repeated measures identified significant differences in the ranked data. Pairwise multiple comparisons were then performed on the ranked data with the Tukey Test. Observed power (OP) was calculated to serve as a guide for future sample size selection for similar studies. All statistical treatments were performed using SigmaPlot 11.0 (Systat, Chicago, Illinois).

3. Results

3.1. Spatiotemporal characteristics

Participants' average and standard deviation comfortable walking speed of 80.0 ± 8.2 m/min resulted from an average stride length of 1.50 ± 0.12 m and cadence of 54 ± 8 strides/min. While stride length was longer for walking compared with all ellipticals, the number of elliptical cycles per minute was similar to walking. Stride lengths and cadence during elliptical training were 1.20 ± 0.10 m and 54 ± 8 cycles/ min for SportsArt, 1.11 ± 0.09 m and 55 ± 6 cycles/min for Life Fitness, 1.10 ± 0.06 m and 54 ± 7 cycles/min for Octane, and 1.14 ± 0.11 m and 56 ± 7 cycles/min for True, respectively.

Table 1 Heel maximum force, peak pressure, and pressure-time integral during walking and elliptical training.[a]

Activity	*MF (N)*	*PP (kPa)*	*PTI (kPa*s)*
Walking	522 (98)	190 (34)	51 (11)
SportsArt	343 (108)	129 (37)	53 (24)
Life Fitness	296 (124)	116 (45)	38 (22)
Octane	336 (161)	124 (46)	41 (16)
True	226 (76)	89 (25)	22 (10)
Significant	W > T, L, O, S	W > T, L, O, S	S, W > T
Main effect	S, O > T	S, O > T	
	$p < 0.001$, $F = 18.02$	$p < 0.001$, $F = 16.02$	$p < 0.001$, $F = 7.03$
	OP > 0.99	OP > 0.99	OP = 0.98

Abbreviations: MF, maximum force; PP, peak pressure; PTI, pressure-time integral; W, overground walking; S, SportsArt Fitness E870; L, Life Fitness X7; O, Octane Fitness Pro4500; T, True Fitness Technology TSXa; OP, observed power.

a. Values presented as mean (standard deviation).

3.2. Heel (Table 1)

MF was significantly higher under the heel during walking compared with all elliptical conditions ($p < 0.001$ for all pairwise comparisons). MF was also significantly higher while exercising on SportsArt and Octane compared with True ($p = 0.003$ and $p = 0.005$ for pairwise comparisons, respectively). PP under the heel followed the same pattern and was significantly elevated during walking compared with all elliptical conditions ($p < 0.001$ for all pairwise comparisons). Additionally, PP was significantly higher while on SportsArt and Octane compared with True ($p = 0.003$ and $p < 0.01$, respectively). Lastly, PTI under the heel region was significantly greater when exercising on SportsArt and during walking compared with True ($p < 0.001$ for both pairwise comparisons).

3.3. Arch (Table 2)

MF did not differ significantly under the arch across conditions. PP under the arch was significantly elevated during walking compared with True ($p < 0.001$), SportsArt ($p < 0.001$), and Life Fitness ($p = 0.004$). Lastly, PTI was significantly greater during walking compared with True ($p < 0.001$), Life Fitness ($p < 0.001$), and SportsArt ($p = 0.002$).

Table 2 Arch maximum force, peak pressure, and pressure-time integral during walking and elliptical training.[a]

Activity	*MF (N)*	*PP (kPa)*	*PTI (kPa*s)*
Walking	198 (68)	98 (21)	40 (13)
SportsArt	202 (83)	73 (21)	28 (9)
Life Fitness	208 (105)	76 (25)	28 (8)
Octane	238 (102)	88 (35)	34 (18)
True	204 (89)	72 (27)	26 (12)
Significant	NS	W > T, S, L	W > T, L, S
Main effect	$p = 0.34$, $F = 1.18$	$p = 0.003$, $F = 4.98$	$p = 0.002$, $F = 5.40$
	OP = 0.08	OP = 0.87	OP = 0.91

Abbreviations: MF, maximum force; PP, peak pressure; PTI, pressure-time integral; W, overground walking; S, SportsArt Fitness E870; L, Life Fitness X7; O, Octane Fitness Pro4500; T, True Fitness Technology TSXa; NS, not significant; OP, observed power.

a. Values presented as mean (standard deviation).

Table 3 Forefoot maximum force, peak pressure, and pressure-time integral during walking and elliptical training.[a]

Activity	*MF (N)*	*PP (kPa)*	*PTI (kPa*s)*
Walking	244 (214)	241 (46)	64 (10)
SportsArt	211 (139)	147 (49)	74 (14)
Life Fitness	218 (165)	155 (50)	81 (28)
Octane	239 (215)	164 (52)	78 (23)
True	204 (151)	162 (53)	82 (27)
Significant	NS	W > S, L, T, O	NS
Main effect	$p = 0.13$[b], $X^2 = 7.14$	$p < 0.001$, $F = 7.57$	$p = 0.08$, $F = 2.28$
	OP = 0.24	OP = 0.99	OP = 0.35

Abbreviations: MF, maximum force; PP, peak pressure; PTI, pressure-time integral; W, overground walking; S, SportsArt Fitness E870; L, Life Fitness X7; O, Octane Fitness Pro4500; T, True Fitness Technology TSXa; NS, not significant; OP, observed power.

a. Values presented as mean (standard deviation).

b. Indicates the use of (median) ranks and the presentation of Chi-square (X^2) due to data not meeting normality assumption.

3.4. Forefoot (Table 3)

MF did not differ significantly under the forefoot across conditions. PP under the forefoot was significantly elevated during walking compared with all elliptical conditions ($p < 0.001$ for all pairwise comparisons). Lastly, PTI did not differ significantly across conditions; however, a trend ($p = 0.08$) was noted towards greater PTI during exercising on True and Life Fitness compared with walking.

4. Discussion

Different mechanical designs across elliptical devices promote distinct lower extremity movement patterns [9], providing impetus for this systematic pilot investigation of their impact on plantar pressures to guide clinical/prevention programs. Considering the underlying force and the resultant pressure under the different regions of the foot, elliptical training appears to be a safer option compared with overground walking. However, when cumulative pressure under the foot is of concern, particularly under the forefoot, exercise should proceed with caution when initiating training on some ellipticals as pressure-time integral exhibited a trend towards exceeding that observed during walking. Our findings contribute to the implementation of safer and appropriate intervention plans regarding musculoskeletal and cardiorespiratory gains with distinct elliptical devices for individuals requiring podiatric care.

4.1. Heel

Consistent with our first hypothesis, lower forces and peak pressures were observed under the heel during use of each elliptical compared with overground walking. Although a 34% variation in maximum force and 31% in peak pressure were recorded across ellipticals, force and pressure values during elliptical training were still far below those observed during walking (43% and 40% lower, respectively). These findings are in agreement with previous work reporting lower peak pressure under the heel when exercising on an elliptical device compared with walking [10], suggesting that the constant double-limb support during the elliptical cycle likely minimizes peak pressures expected under the heel. When considering short bouts of elliptical exercise, the models used in our study can provide protective benefits compared with walking when orthopedic conditions to the heel, such as subcalcaneal spurs, are of concern.

Contrary to our second hypothesis, differences in cumulative heel pressure were detected between walking and elliptical training. Interestingly, exercising on the True exhibited a significantly lower heel pressure-time integral (~57%) compared with walking. The larger peak pressure under the heel during walking likely led to such findings, as the peak pressure generated onto the outstretched limb during the initial contact of gait could have largely contributed to the cumulative pressure under the heel across the gait cycle. It is important to note that a large variation in pressure-time integrals across elliptical models was observed (range of 31 kPa*s), with the SportsArt pressure-time integral exceeding True's by more than two-fold. While we intentionally chose elliptical machines that promoted movement patterns observationally close to walking, minor differences in the design may have contributed to the pressure profile differences observed across devices. For example, the SportsArt had a longer vertical pedal excursion than the other ellipticals evaluated; True was the only elliptical with its flywheel located under the user, whereas the other machines' flywheels were located either in front or behind the foot pedals. The impact of the design features on plantar pressure requires further study. However, the overall findings suggest that exercising on Life Fitness, Octane, and True ellipticals may promote lower cumulative heel pressure than walking. Additionally, use of the SportsArt would be expected to provide a more similar pressure-time integral to walking while still diminishing the maximum force experienced by the heel during limb loading [14].

4.2. Arch

Average peak pressure was 25% lower during exercise on the True, SportsArt, and Life Fitness ellipticals compared with walking even though maximum force under the arch was similar across conditions. This lower peak pressure likely occurred due to a larger contact area for force distribution under the arch at the instant of peak pressure during elliptical training compared with walking [15]. This again could be the result of subtle differences in machine design. In addition, three patterns of foot-pedal contact during elliptical usage were observationally apparent as participants trained, including the entire foot maintaining contact, heel rising near the posterior portion of the elliptical cycle, and a combination of the previous two patterns across strides. Whether the subtle differences in machine design or ankle joint flexibility dictates these differences in movement patterns should be explored in future studies. In contrast to our second hypothesis, cumulative pressure under the arch was not similar between elliptical training and walking. Similar to the findings for the heel, the larger peak pressure observed under the arch during walking compared with the elliptical conditions likely explains walking's larger pressure-time integral.

The mask representing the arch in our study included the tarsal bones and the proximal portion of the metatarsals (Fig. 2). Injuries to this region, more specifically to the medial cuneiform-fifth metatarsal region such as Lisfranc injuries, can emerge from low-energy trauma during leisure or elite athletic activities. This type of injury typically occurs with gymnastics and football athletes and can lead to serious morbidity hindering return to sport at pre-injury level [16,17]. Our findings that peak pressure and pressure-time integral under the arch were larger during walking than elliptical training suggest that the latter activity may be a safer rehabilitation option for cardiorespiratory fitness compared with overground walking when protection of plantar load sensitive structures in the arch is warranted.

4.3. Forefoot

While maximum force under the forefoot was not different across conditions (in contrast to our first hypothesis), peak pressure was 32%–39% lower during elliptical training compared with walking. During gait's terminal single limb support period, body weight progresses onto the forefoot as the heel rises from the ground to maximize gait efficiency and promote contralateral step length [18]. In contrast, the shortened step length and sustained double-limb support of elliptical training likely reduced the need to fully elevate the heel.

Despite significantly lower peak pressures under the forefoot during each elliptical condition compared with walking, pressure time-integrals in the forefoot region were ~20% larger while elliptical training. This pattern points to the impact of elliptical training's sustained double limb support on forefoot pressure-time integral. Additionally, while True and Life Fitness exhibited 22% and 21% larger pressure-time integral than walking, SportsArt was only 14% larger than walking. These findings suggest that short sessions of elliptical training may be appropriate when protection from sustained pressure under the forefoot is required, as observed with common orthopedic conditions such as metatarsalgia or sesamoiditis.

4.4. Overall findings

The current study compared the impact of elliptical training at a self-selected speed on four ellipticals and walking on plantar pressures in young adults. Although 6 out of 9 comparisons exhibited large observed power, other comparisons were underpowered. This likely occurred due to the large variation (standard deviation) within condition, as seen with forefoot maximum force. Since no prior work existed to determine *a priori* sample size, our findings provide guidance for future studies when considering the appropriate sample size for similar analyses. For instance, *a posteriori* sample size calculation determined that 33 (pressure-time integral under the forefoot) to 82 (maximum force under the arch) individuals were needed to provide adequate power (minimum of 80%, alpha set at 0.05) to detect differences across conditions that did not achieve significance. Additionally, we are aware of the potential bias generated by asking participants to use their own shoes. Differences in shoe structure (e.g., wear patterns or thicker *vs* thinner shock absorption insoles across plantar areas) could lead to distinct lower extremity mechanics, altering plantar pressure distribution. Future work should consider evaluations that include a similar footwear model across participants to reduce such bias. Furthermore, this foundational work was performed with individuals without disabilities. The authors are aware that those with podiatric and/or chronic conditions may adopt antalgic gait patterns and exercise differently on gait-training devices, potentially changing plantar pressure patterns. Thus, our findings may be used with caution and future studies with patient populations should compare findings with our work. Lastly, given the popularity of high intensity interval training approaches, it would be of value to understand the impact of increasing training intensity through the application of resistance or increased speed on plantar pressures.

5. Conclusion

Ellipticals can be used therapeutically as certain models can promote gait-like activity while targeting musculoskeletal health and cardiorespiratory fitness. For most of the variables investigated, plantar pressures were lower when exercising on the ellipticals compared with walking. Consideration should be given to which elliptical to incorporate into therapeutic/aerobic exercise programs for young adults with podiatric conditions since pressure profile, including maximum force, peak pressure, and pressure-time integral, varied across elliptical models under key plantar regions of the foot.

Brief summary

- Recurring exposure to elevated plantar impact forces during overground activities has been associated with podiatric orthopedic conditions.
- Exercising on elliptical devices promote safer plantar pressure profiles than overground training (e.g., walking, running).
- Distinct mechanical design features of commercial elliptical models alter trajectories of pedal excursion and, consequently, body posture when exercising.
- Different elliptical models rendered distinct maximum force and peak pressure profiles under the heel.
- Cumulative plantar pressure was not consistently lower on ellipticals compared with walking.
- Clinicians should carefully consider options and patients' response when selecting a device for training for those requiring foot care.

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Conflict of interest The author G. M. Cesar declares no conflict of interest. For the authors J. M. Burnfield and T. W. Buster, three patents (2 US and 1 Canadian) have been issued for a motor-assisted elliptical that was developed in association with the above referenced grant. The patented technology has been licensed to SportsArt for commercial distribution and any sales could lead to a royalty distribution. SportsArt manufactured one of the ellipticals discussed in this research study.

Author contribution All three authors made substantial contributions to the presented work, including conception and design of the study (JMB, TWB), acquisition of data (TWB), analysis and interpretation of data (GMC, TWB, JMB), drafting the article (GMC), critically contributing to its intellectual content (GMC, JMB, TWB), and final approval of the version to be submitted (GMC, TWB, JMB).

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