Clinical Implications of Changing Parameters on an Elliptical Trainer

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Background: Specific weightbearing instructions continue to be a part of routine orthopaedic clinical practice on an injured or postoperative extremity. Researchers and clinicians have struggled to define the best weightbearing strategies to maximize clinical outcomes.

Purpose: To investigate the average percentage body weight (APBW) values, weightbearing distribution percentages (WBDP), and cadence values on the entire foot, hindfoot, and forefoot during changing resistance and incline on an elliptical trainer, as well as to suggest clinical implications.

Study Design: Descriptive laboratory study.

Methods: An original research study was performed consisting of 30 asymptomatic subjects (mean age, 29.54 ± 12.64 years; range, 21-69 years). The protocol included 3 consecutive tests of changing resistance and incline within a speed range of 70 to 95 steps/min. The SmartStep weightbearing gait analysis system was utilized to measure the values.

Results: The APBW values for the entire foot ranged between 70% and 81%, the hindfoot values were between 27% and 57%, and the forefoot values between 42% and 70%. With regard to WBDP, the forefoot remained planted on the pedal (stance phase) 2 to 3 times more as compared with the hindfoot raise in the swing phase.

Conclusion: The study findings highlight the fact that elliptical training significantly reduces weightbearing in the hindfoot, forefoot, and entire foot even at higher levels of resistance and incline.

Clinical Relevance: Weightbearing on the hindfoot consistently displayed the lowest weightbearing values. Orthopaedic surgeons, now equipped with accurate weightbearing data, may recommend using the elliptical trainer as a weightbearing exercise early on following certain bony or soft tissue pathologies and lower limb surgical procedures.

Keywords: body weight; weight distribution; elliptical parameters; weightbearing

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Specific weightbearing instructions continue to be a part of routine orthopaedic clinical practice on an injured or postoperative extremity following certain bony or soft tissue pathologies and lower limb surgical procedures (eg, microfracture, cartilage transplantation).[3] Studies supporting weightbearing restriction are based on several histopathology principles related to the bone healing processes after fracture or surgery as well as the fear that excessive weight on an injured or operative site will lead to implant failure, and therefore affect fracture stability and alignment.[9,23] Conversely, the rationale for advancing weightbearing is that repetitive loads can stimulate osteoblastic activity in fracture patterns and fixation constructs in load-bearing extremities.[12,22] Improved understanding of postoperative weightbearing and standardization in outcomes studies could greatly affect both patient and surgeon satisfaction in postoperative partial weightbearing care.[14]

Some researchers have argued that weightbearing limitations are not even necessary in many clinical scenarios, as patients will self-limit their weightbearing because of pain in the postoperative period.[6] Studies have shown that patients with lower leg fractures who exceeded their permitted weightbearing range by up to 60% exhibited no short- or long-term complications.[13,16] Early return to physical activity in general and lower limb strengthening and range of movement activities in particular have been

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The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.

The Orthopaedic Journal of Sports Medicine, 2(6), 2325967114535553
DOI: 10.1177/2325967114535553

TABLE 1
Study Cohort Characteristics

	n	Weight, kg			Age, y		
		Average	Range	Standard Deviation	Average	Range	Standard Deviation
Males	12	72.38	62-79	5.01	24.77	23-30	2.22
Females	18	63.87	53-103	13.13	31.33	21-69	14.91
All	30	66.71	53-103	11.70	29.54	21-69	12.64

found to be important in minimizing the known complications of prolonged nonweightbearing and immobilization.[1,4,10]

Despite the growing popularity of elliptical exercise (EE) in recent years and its suitability to accommodate persons with varying levels of disease severity due to its self-paced, fluid, nonjarring motion, as well as the machine's adjustable incline and resistance levels, little is known regarding the actual loadings applied to the body during EE and how these parameters influence the average percentage body weight (APBW) and the weightbearing distribution percentage (WBDP). APBW may be defined as the average value of the measured ground reaction of subjects, expressed as a percentage of the total body weight. WBDP refers to the percentage time that the participants spent weightbearing in the stance phase (when the foot is on the pedal) as compared with the time spent in the swing phase (when the hindfoot is raised during the cyclical motion).

Although it may seem apparent that EE may have reduced weightbearing compared with treadmill or level ground exercise (both feet are in contact with the pedal surface the entire time), no previous study has investigated the actual APBW, WBDP, and cadence values on the entire foot, hindfoot, and forefoot during changing resistance and incline on an elliptical trainer. This, then, is the objective of this study.

METHODS

Thirty asymptomatic subjects were voluntarily recruited (Table 1). Exclusion criteria included surgery of the hip, knee, or ankle/foot less than 2 years previously as well as objective symptoms of pain or disability in the hip, knee, or ankle/foot joints for at least a 3-month period prior to testing. Helsinki Ethics Committee approval as well as written consent from all subjects was obtained prior to testing.

For the purposes of measuring weightbearing parameters, the SmartStep system (Andante Medical Devices Ltd) was used (Figure 1). The SmartStep pneumatic insole system measures key gait parameters during ambulation.

Prior to each test, 1 SmartStep portable microprocessor control unit was fitted around 1 lower leg. The test measurements were conducted on 1 elliptical trainer (Precor 576i EFX; Precor Inc). The testing conditions were identical for all subjects tested. The authors decided to investigate the weightbearing changes at varying parameters of resistance and incline as individuals tend to use varying parameters while exercising on the elliptical trainer.

Figure 1. The computerized air-insole auditory biofeedback system (SmartStep).

The study protocol included 3 sets of tests:

Test 1: Resistance and incline paired together in increasing order at the set device levels of 1, 5, 10, 15, and 20.
Test 2: Resistance held constant at level 1, while incline increased from levels 1 to 20 in increments of 5.
Test 3: Incline held constant at level 1, while resistance increased from levels 1 to 20 in increments of 5.

A 20-second time period was recorded for each set of parameters. The recording was measured only when the subjects exercised within a speed range of 70 to 95 steps/min. To standardize the research methodology as well as ensure that the results obtained were related solely to lower body weightbearing, subjects were not permitted to hold the side handles for support. The examiners stood close by on both sides of the participants to minimize the risk of loss of balance. All participants were free to choose the running shoes of their own preference. The physical testing conditions were identical for all subjects tested.

The 1-sample significance 2-tailed *t* test was used to compare differences in APBW values on the entire foot, hindfoot, and forefoot between the changing parameters within the 3 sets of tests. The independent-samples *t* test was used to compare between sexes. The APBW values were compared statistically, and not the average peak values obtained. Statistical analysis was undertaken via the use of the SPSS predictive analytics software package (v 18.0; IBM Corp). The *P* value of statistical significance was <.05.

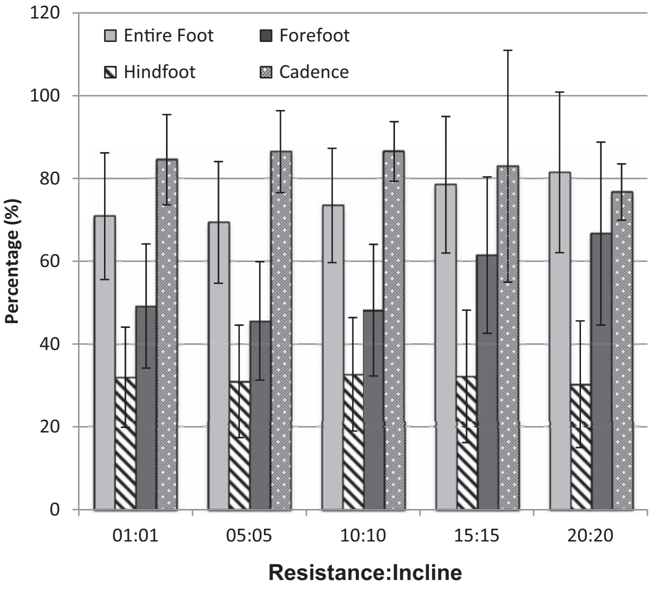

Figure 2. Average percentage body weight versus increasing resistance and incline.

RESULTS

Six participants (20%) failed to comply with the test criteria and were therefore not included in the data analysis.

In test 1, where both resistance and incline increased, there was a highly significant APBW value difference for the entire foot and forefoot ($P < .0001$) (Figure 2). In test 2, where the resistance remained constant and the incline increased, there was no significant APBW value difference noted (Figure 3). In test 3, where the resistance increased and the incline remained constant, there was a highly significant APBW value difference for the entire foot, hindfoot, and forefoot ($P < .0001$) (Figure 4). Table 2 demonstrates the actual APBW values of all 3 tests with their standard deviations.

All the APBW values were significantly lower than full weightbearing ($P < .05$), irrespective of the changing resistance and incline parameters. Weightbearing on the hindfoot consistently displayed the lowest values, significantly lower than the entire foot and forefoot APBW values ($P < .05$), registering approximately one-third of full body weight on all changing parameters except at the 2 highest resistance positions (15 and 20).

With regard to WBDP (stance/swing phase ratios), the foot was 2 to 3 times more in the stance phase as compared with the swing phase, which only occurs in the hindfoot (Table 2). The cadence levels were not significantly different during the tests ($P < .05$). There were no statistically significant differences noted pertaining to APBW values and WBDP between the sexes ($P > .05$).

DISCUSSION

The main study findings highlight that elliptical training significantly reduces weightbearing in the hindfoot, forefoot, and entire foot, even at higher levels of resistance and incline. This paper now quantifies for the first time these reductions during changing incline and resistance. Knowing these parameters may assist the medical team when having to make reliable clinical decisions in relation to when injured or surgically operated athletes may return to weightbearing sporting activities.

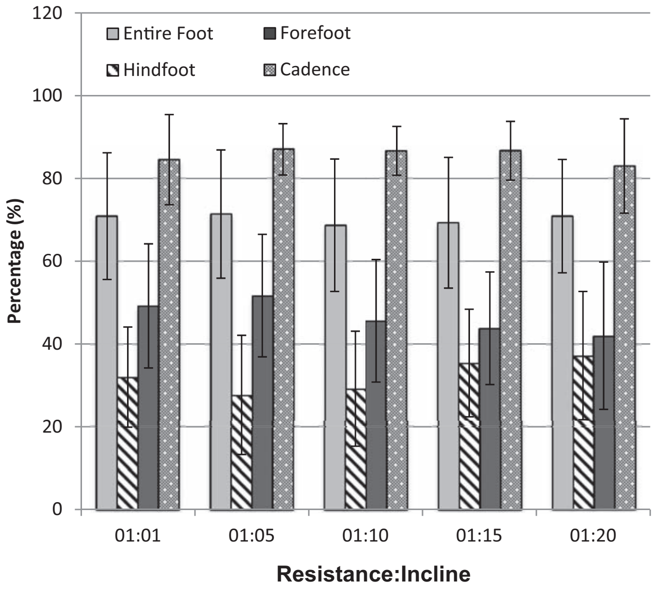

Figure 3. Average percentage body weight versus constant resistance and increasing incline.

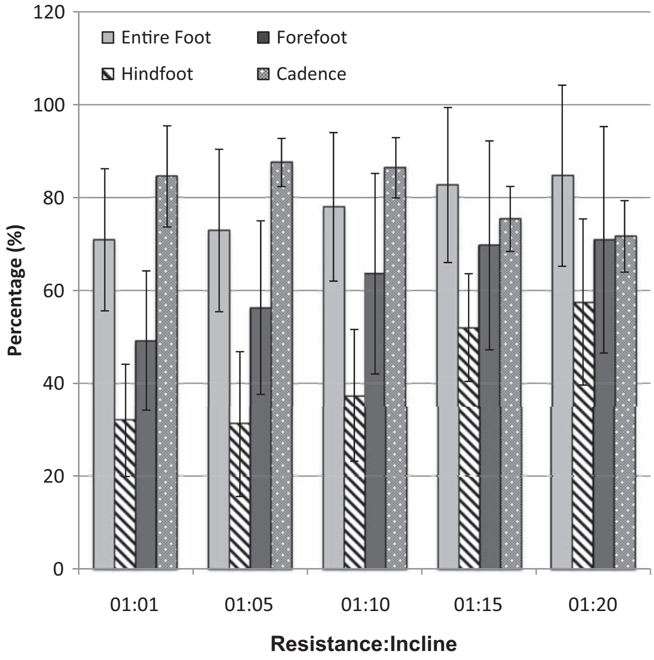

Figure 4. Average percentage body weight versus increasing resistance and constant incline.

TABLE 2
APBW Values, Hindfoot/Forefoot and Stance/Swing Ratios, and Cadence Values[a]

Resistance: Incline	APBW Value[b]			Hindfoot/Forefoot Ratio	Stance/Swing Phase Ratio, %	Cadence, Steps/Min[b]
	Entire Foot	Hindfoot	Forefoot			
Test 1						
01:01	70.9 ± 15.3	32.0 ± 12.1	49.2 ± 15.0	1:1.5	76:24	84.55 ± 10.9
05:05	69.4 ± 14.7	31.0 ± 13.6	45.6 ± 14.3	1:1.5	74:26	86.49 ± 9.9
10:10	73.5 ± 13.8	32.7 ± 13.7	48.2 ± 15.9	1:1.5	68:32	86.54 ± 7.2
15:15	78.5 ± 16.5[c]	32.2 ± 16.0	61.5 ± 18.9[c]	1:1.9	64:36	82.98 ± 0.28
20:20	81.5 ± 19.4[c]	30.3 ± 15.3	66.7 ± 22.1[c]	1:2.2	65:35	76.74 ± 6.8
Test 2						
01:01	70.9 ± 15.3	32.0 ± 12.1	49.2 ± 15.0	1:1.5	76:24	84.55 ± 10.9
01:05	71.4 ± 15.5	27.7 ± 14.4	51.7 ± 14.8	1:1.9	66:34	87.04 ± 6.2
01:10	68.7 ± 16.0	29.2 ± 13.9	45.6 ± 14.8	1:1.6	70:30	86.68 ± 5.9
01:15	69.3 ± 15.8	35.4 ± 13.0	43.8 ± 13.6	1:1.2	72:28	86.70 ± 7.1
01:20	70.9 ± 13.7	37.2 ± 15.5	42.0 ± 17.8	1:1.1	75:25	83.01 ± 11.4
Test 3						
01:01	70.9 ± 15.3	32.0 ± 12.1	49.2 ± 15.0	1:1.5	76:24	84.55 ± 10.9
05:01	72.9 ± 17.5	31.2 ± 15.6	56.3 ± 18.7	1:1.8	68:32	87.55 ± 5.2
10:01	78.0 ± 16.0[c]	37.4 ± 14.2	63.6 ± 21.6[c]	1:1.7	68:32	86.41 ± 6.5
15:01	82.7 ± 16.7[c]	52.0 ± 11.6[c]	69.7 ± 22.5[c]	1:1.3	64:36	75.40 ± 7.0
20:01	84.7 ± 19.5[c]	57.5 ± 17.9[c]	70.9 ± 24.4[c]	1:1.2	64:36	71.63 ± 7.7

[a] APBW, average percentage body weight.
[b] Data are expressed as actual value ± standard deviation.
[c] $P < .0001$.

Most of the previous literature comparing different exercise machines have investigated electromyography patterns[5,24]; biomechanics; kinematics[2,27]; comparisons between elliptical training, stationary cycling, treadmill walking, and over-ground walking[7,24]; ground reaction forces[21]; and the effect of pedal rates on loading.[5] Use of the elliptical trainer for athletic and rehabilitative training would have to consider users' joint function and muscle strength, especially at the knee, to avoid injuries.[21] Elliptical training demonstrated greater rectus femoris activity and greater rectus femoris/semitendinosus coactivation when compared with stationary cycling, treadmill walking, and over-ground walking. These results may assist in selecting the most appropriate training device for specific patients.[25] Treadmill walking most closely resembled over-ground walking with near overlap, reinforcing its appropriateness for gait training. When comparing over-ground walking versus treadmill versus cycling versus elliptical exercise, cycling showed the largest gait deviation index difference from over-ground walking, with the elliptical closer but still a significant distance from all 3. Cycling showed greater hip reciprocation. Cycling and elliptical exercise showed stronger intralimb synergism at the hip and knee than the other 2. Based on kinematics, results suggest that elliptical training may have greater transfer to over-ground walking than cycling, and cycling may be more useful for enhancing reciprocal coordination.[7] In the only other previously published article[17] evaluating APBW values in EE as well as comparing it with other activities, it was found that EE significantly reduces APBW as compared with ground walking, over-ground jogging, and treadmill jogging. In this study, however, EE was measured at only a single parameter setting (10:10) and therefore does not reflect APBW changes during changing parameters, this being the main objective of this study.

The elliptical motion of the elliptical trainer may explain why there is significantly reduced weightbearing on the lower limb as opposed to the vertical forces that occur during walking and running. Repetitive loads can stimulate osteoblastic activity in fracture patterns and fixation constructs in load-bearing extremities.[21] This has particular significance to orthopaedic surgeons and rehabilitation personnel, who may utilize this information to recommend using the elliptical trainer, even at increasing resistance and incline, in conditions necessitating specific weightbearing limitations involving the lower limb and especially the foot and ankle. The general trend noted from all the changing parameters tested was that increasing resistance resulted in a corresponding increase in all APBW values. This may have occurred due to the additional force that has to be placed through the mid/forefoot to maintain the required speed as resistance increases. On the other hand, incline changes with constant resistance did not appear to influence the APBW values.

During elliptical training, the mid/forefoot remains planted on the pedal (stance phase) continuously throughout the elliptical motion, while the hindfoot has a distinct stance and lift (swing) phase. The percentage of time spent in the stance phase was 2 to 3 times greater than that of the swing phase. When analyzing these 2 issues together, it may be understood that the constant force exerted by the mid/forefoot during the transfer from midstance through heel-off results in additional pressure, thus ensuring continuous forward propulsion on the pedals and enabling a continuous elliptical motion. Despite this, the mid/forefoot APBW value did not exceed 70% of body weight.

The standard deviation for the APBW values at all levels was high (Table 2), especially at the higher resistance/incline levels. This highlights the large pedal stride variability between subjects tested. Six participants (20%) failed to comply with the test criteria. Four were unable to use the elliptical trainer without holding onto the side handles, and 2 did not have separate heel and forefoot values (ie, they did not raise their heel during elliptical training), and thus the SmartStep apparatus could not measure hind/forefoot values.

The average age of the study participants in this study was young (29.54 years). Previous studies have noted significant biomechanical variables in the gait patterns of the fit and the healthy elderly compared with those of young adults.[26] Aging can lead to several physical changes that affect the gait process.[6] Studies have found that muscle strength is directly associated with gait velocity,[11] and that as speed decreases, more time is spent in the stance phase. Muscle mass, strength, and contractility are commonly known to decline with advancing age.[19] Although there are several perceived subjective and temporal differences between the sexes with regard to human gait (females walk with lesser step width and more pelvic movement[18]), no observed sex differences were noted on elliptical training with respect to APBW values, WBDP, and stance/swing phases. This may be understood by the fact that the main parameter tested was the APBW placed on the surface, and not the actual body weight itself.

The main advantage of the SmartStep system lies in its ability to measure weightbearing parameters in various functional settings, for example, walking, running, and stair negotiation.[8,15] Other laboratory measuring devices, for example, the balance plate system (Neurocom; Natus Medical), the force plate platform (AMTI; Advanced Mechanical Technology Inc) and the emedR-c50 (novel GmbH), are expensive, with measurement apparatuses that are not commonly portable. Additionally, they are not readily available in clinical and rehabilitation settings and cannot be adapted for use in popular sporting activities such as ground jogging, treadmill jogging, and elliptical exercise.

Limitations

Due to the current technological limitations of the SmartStep system, weightbearing results cannot be detected for more than approximately 130 kg. As a result, only individuals whose actual body weight did not exceed 100 kg were tested on the elliptical trainer. This limitation should not influence the results as the values gained are not the actual participants' weights but rather the APBW values. The referent APBW values for a heavier population should therefore be the same. The specific design of the air-filled insoles of the SmartStep system only allows for weightbearing measurements in the sagittal plane (hindfoot and forefoot) and therefore precludes measurements in the functional coronal plane (supination and pronation). As a consequence, the study results are limited to hindfoot and forefoot measurements only. Each test took approximately 20 minutes to conduct on 1 leg, and due to the participants' preferences, only 1 limb was measured per test.

The authors chose very specific speed parameters for use in the study (70-95 steps/min), as this reflects a commonly used speed range parameter. Further studies should investigate the influence of changing speeds on APBW values, WBDP, and stance/swing ratios. The results from this article are therefore only applicable to EE without-handle use.

The actual resistance values at different parameters may differ between elliptical trainers. The resistance of the elliptical trainer may be measured by using a handheld force sensor while measuring velocity to estimate damping ratios. These measurements were not possible within the scope of this study.

It was not within the scope of this study to measure the shear forces in the hip, knee, and ankle during elliptical motion and changing parameters. This may be of significance when recommending elliptical exercise, especially at higher inclines and resistance, in cases where shear forces may be detrimental to the particular pathology or following a surgical procedure. When comparing over-ground walking with treadmill walking, the anterior-posterior and vertical components of the ground reaction forces were very similar.[20] In a healthy population comparable to that in this study, there was no statistical difference when evaluating joint moments and ground reaction forces in both over-ground walking and treadmill training.[28] On the other hand, elliptical training requires greater flexion of the hip and knee along with increased dorsiflexion compared with over-ground walking.[21] While the vertical pedal reaction force decreases the joint moments in the frontal and transverse planes, there is a concomitant increase in the joint moment of the sagittal plane components, requiring a greater knee and hip extensor moment; in turn, this increases the load on the quadriceps and hamstrings.[21] In addition, elliptical training affects the joint centers and line of the pedal reaction force, ultimately affecting moments at the lower limb.[21] This research suggests that joint function and muscle strength in patients should be taken into consideration due to changing forces on the joints.

Further studies may include an accompanying biomechanics study involving kinematic and kinetic analyses as well as evaluating ground reaction forces in the tested activities. These measurements were not within the scope of this study. A future study should include more elderly participants, subgrouping by age. It may be of interest to analyze whether age plays a role in the hindfoot/forefoot APBW, WBDP, and stance/swing phase percentage ratios.

CONCLUSION

This original research study has shown that exercising on the elliptical trainer, irrespective of changing resistance and incline parameters, resulted in significantly lower APBW values when compared with full weightbearing. Elliptical training may therefore be instituted very early on following certain lower limb pathological conditions and surgical procedures, where partial weightbearing is permitted and encouraged. APBW values of individuals using the elliptical trainer seem somewhat variable, and high shear forces may exist on the lower limb joints on high resistance. Therefore, caution must be taken when advising the use of the elliptical trainer in specific medical cases.

ACKNOWLEDGMENT

The authors would like to thank Mrs Tali Bdolah, MSc, senior statistician, Hebrew University, Jerusalem, for her assistance in the statistical analyses, as well as Mrs Sari Diament, BSc, for editing and reviewing this study.

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