Clinical Biomechanics 27 (2012) 738–743

Contents lists available at SciVerse ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

How do elliptical machines differ from walking: A study of torso motion and muscle activity

Janice M. Moreside [a], Stuart M. McGill [b],*

[a] Dalhousie University, Canada
[b] University of Waterloo, Canada

ARTICLE INFO

Article history:
Received 6 December 2011
Accepted 27 March 2012

Keywords:
Spine kinematics
Elliptical trainer
Trunk muscle activation patterns

ABSTRACT

Background: The elliptical trainer is a popular exercise modality, yet its effect on the lumbar spine is poorly understood. The purpose of this study was to analyze the effect of different hand positions, speed and stride lengths on spine kinematics and corresponding muscle activity while using the elliptical trainer, and compare with those demonstrated in normal walking.

Methods: Electromyographic data was collected over 16 trunk and gluteal muscle sites on 40 healthy males (mean age (SD) = 23(3)) while on the elliptical trainer. Two stride lengths (46, 66 cm), 2 speeds (self-selected, 30% faster), and 3 hand positions (freehand, central bar, handles) were analyzed. Lumbar spine kinematics was calculated from data collected using a motion capture system. Results were compared to those found in walking using repeated measures ANOVA for each dependent variable with Bonferroni adjustments ($P<0.004$. Correlations were made between lumbar motion and various anthropometric measures.

Findings: All significance levels comparing walking to elliptical varied according to stride length, speed and hand position. Average lumbar flexion angles and lumbar rotation were generally greater on the elliptical trainer, whereas walking produced more frontal motion. Total lumbar flexion/extension was similar between the two activities. Muscle activation patterns of the gluteal muscles were consistently higher on the elliptical, whereas the back extensors, latissimi and internal obliques were greater in only selected conditions.

Interpretation: The various hand positions, speeds and stride lengths affect lumbar motion and muscle activity on the elliptical trainer, thus must be considered when incorporated into an exercise protocol.

1. Introduction

The elliptical trainer has gained popularity in recent years due to its relatively low impact requirements, with a metabolic cost similar to treadmill running (Mier and Feito, 2006). The kinematics involved with elliptical use, however, is less well understood. Anecdotally, there are mixed reviews as to the effect of the elliptical trainer on the lumbar spine. While some people use it regularly with no ill effects, others claim that it provokes low back pain.

Despite its widespread use, there is little quantitative literature as to the effect of the elliptical trainer on the lumbar spine. Burnfield et al. (2010) describe increased lumbar flexion and a corresponding decrease in lumbar extension when comparing the elliptical to walking. Such a posture is known to increase intra-discal pressures (Adams and Hutton, 1980; Nachemson and Morris, 1964) and thus may be a precursor to intervertebral disc damage (Aultman et al., 2005; Gunning et al., 2001) and/or low back pain (Punnett et al., 1991). Repeating this motion in a cyclic manner increases the likelihood of annular failure (Callaghan and McGill, 2001; Gordon et al., 1991) as does the addition of axial torsion (Adams and Hutton, 1981; Drake and Callaghan, 2009; Drake et al., 2005; Marshall and McGill, 2010), both of which appear to be present on the elliptical trainer. Of equal interest is the effect that various hand positions, velocities, and stride lengths have on lumbar kinematics. Although the elliptical trainer is generally presented as an exercise machine with concurrent arm and leg activity, anecdotal evidence suggests that many users will either not use the oscillating handles, thereby going “freehand” or will choose to hold onto a stationary bar situated at approximately waist height in front of them. Constraining arm motion to the torso during gait is known to result in a decrease in lumbar rotation (Callaghan et al., 1999) whereas a slower cadence increases the lumbar flexion angle (Callaghan et al., 1999). However, little is known about the effect that holding onto an anterior support structure would have on the lumbar spine, as would be seen on the elliptical trainer. Thus, there may not be one simple answer as to lumbar motion on the elliptical trainer; other variables such as speed, arm position or stride length may affect the outcomes, and should be parsed out. Muscle activation levels produced on the elliptical trainer are also not well understood. To date, researchers have focused on the lower extremities, documenting peak activation amplitudes between 38% and 42% MVC for Gluteus Maximus (GMax), and 38% to 41% MVC for Gluteus Medius (GMed) on 3 different elliptical trainers, compared to 26% and 38% MVC, respectively, when walking (Burnfield

---

* Corresponding author at: University of Waterloo, 200 University Ave. West, Waterloo, ON, Canada, N2L 3G1.
E-mail address: mcgill@uwaterloo.ca (S.M. McGill).

0268-0033/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2012.03.009

et al., 2010). If present, an increase in trunk muscle activation levels would add to the lumbar compressive forces (Cholewicki et al., 1995; Granata and Marras, 1993; Granata and W.S., 2000; Vera-Garcia et al., 2006) which may already be increased due to the flexed posture of the lumbar spine adopted on the elliptical trainer (Burnfield et al., 2010).

To the best knowledge of the authors, no literature exists which specifically addresses the effect that use of the elliptical trainer has on lumbar spine kinematics and trunk muscle activation patterns. The purpose of this study, therefore, was to analyze the effect of different hand positions, speed and stride lengths on spine kinematics and corresponding muscle activity while using the elliptical trainer, and compare with those demonstrated in normal walking. The hypotheses with regards to elliptical trainer use were: 1) spine kinematics and muscle activation patterns will be different than those found in walking; 2) hand position, stride length and velocity will affect spine motion and muscle activation patterns; 3) anthropometric measurements will affect spine kinematics.

2. Methods

2.1. Participants

Forty healthy males between the ages of 19 and 35 (mean 23(3)) years volunteered for this study. Their mean height was 178(7) cm and mean body mass was 79(13) kg. Participants were recruited from the university community and surrounding area via posters and word of mouth. All claimed to be free of recent or chronic low back or hip pain or other pathology which might have interfered with participation in the study. Each participant completed a written informed consent document approved by the University Office for Research Ethics.

2.2. Electromyography

Surface electromyography signals were collected bilaterally on each subject from the following trunk muscles: rectus abdominis (RA), external oblique (EO), internal oblique (IO), latissimus dorsi (LD), erector spinae at T9 and L4 (T9ES and L4ES, respectively). Electrode position has been previously described (Moreside et al., 2007). In addition, signals were collected from gluteus maximus (GMax), located over the maximal bulk of the muscle belly, approximately mid-buttock; and gluteus medius (GMed), approximately 6 cm caudal to the iliac crest on the posterior-lateral pelvis. Pairs of Ag–AgCl surface electrodes were positioned with an inter-electrode distance of 3 cm. The EMG signals were collected at 2400 Hz, amplified to produce approximately ±2.5 V, then A/D converted (12 bit resolution) at 1024 Hz. EMG signals were full wave rectified and low pass filtered (low pass Butterworth filter) with a cutoff frequency of 2.5 Hz (Brereton and McGill, 1998). A 0.5 s moving average window was used to calculate the maximum EMG amplitude of each muscle across MVC techniques (Vera-Garcia et al., 2010). Maximum EMG values were then used to normalize EMG signals obtained during each MVC manoeuvre, using a custom Labview program (National Instruments Corp, Austin, USA). Maximum EMG values were extracted from the entire capture time of each elliptical and walking trial. MVCs were obtained during 3 second isometric maximal exertion tasks in the following way: for the abdominal muscles, each subject was in a sit up position and manually restrained by a research assistant, who matched the effort so that very little motion occurred. The subject produced a sequence of maximal isometric efforts in trunk flexion, right lateral bend, left lateral bend, right twist and left twist directions, but again with little motion occurring. For the extensor muscles, an isometric trunk extension was resisted with the torso cantilevered over the end of the test table (Biering–Sorensen position). The MVC for GMed was measured with subjects positioned in side lying; the uppermost leg was abducted and slightly externally rotated, with a research assistant resisting maximal isometric efforts of this position. The GMax MVC was performed by resisting hip extension in prone lying with the knee flexed to 90°, although in many instances the maximal activity occurred in the same MVC as the back extensors, thus was chosen for normalization.

2.3. Motion capture

A Vicon MX Motion System and Nexus software (Vicon Motion Systems, Oxford, UK) were used for capturing motion via eight infrared cameras, collecting at a frequency of 60 Hz. Rigid plates with 4 reflective markers on each were attached via elastic straps to body segments bilaterally as follows: shin, thigh, foot, hand, forearm, upper arm, and overlying the midline on the posterior pelvis, T12 and forehead. In addition, single markers for calibration purposes only were attached over the posterior right (Rt) scapula, C7 spinous process, sternal notch, and bilaterally over the medial and lateral aspects of each ankle, knee, wrist, elbow, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), greater trochanters, acromions, and earlobes. The local coordinate system of the pelvis was defined by the markers atop the ASISs and PSISs, with the x, y and z axes being posterior/anterior, right/left and vertical, respectively.

2.4. Elliptical

An Octane (Octane Fitness, Brooklyn Park, MN USA) elliptical trainer was used for this research, as it featured variable stride lengths, yet was felt to represent the type of equipment commonly found in a fitness facility. Participants were invited to practice on the elliptical for as long as necessary prior to data collecting, to ensure basic co-ordination of movement.

2.5. Procedure

All testing occurred in the Human Performance Laboratory at the University of Waterloo. Participants were requested to wear spandex-type shorts, to permit application of the reflective markers on top of the shorts. T-shirts were removed, and they were asked to wear a type of footwear appropriate for running/exercising.

Anthropometric measurements were taken: height, weight, arm length, leg length, as well as numerous pelvis and thorax dimensions for modeling purposes. Hip extension (using the modified Thomas test) was measured with a custom goniometer affixed with a spirit level on each arm, and a blood pressure cuff under the lumbar spine, as per Moreside and McGill (2011). In the addition to segment lengths, the hip extension measurement was collected to determine its predictive value in lumbar motion when on the elliptical trainer. Following MVC collection and application of reflective markers, a calibration posture was captured with the participant standing in anatomical position. Calibration markers were then removed. Motion capture began with the participants being asked to walk at a comfortable pace along the length of the laboratory. This resulted in cadences ranging from 41 to 60 gait cycles per minute (cpm), with the mean being 51(4) cpm, and stride lengths ranging from 56 to 90 cm, with a mean of 74(8) cm. All trials were repeated twice.

Participants were then asked to begin exercising on the elliptical at a self-selected speed: one which they would choose if expecting to exercise for 30 min. This speed varied from 40 to 70 cpm with a mean speed of 53(7) cpm. They were encouraged to practice all 3 hand positions: holding onto the moving handles ("handles"), holding onto a stationary central bar ("bar"), or not holding on at all ("freehand") (Fig. 1). Besides varying hand position, stride length was varied from 46 cm to 66 cm (18 in. to 26 in., respectively) which were the two extremes of the Octane elliptical trainer. Speed was varied from the self-selected speed to one that was 30% faster. Once ready, data collecting moved smoothly from one position to

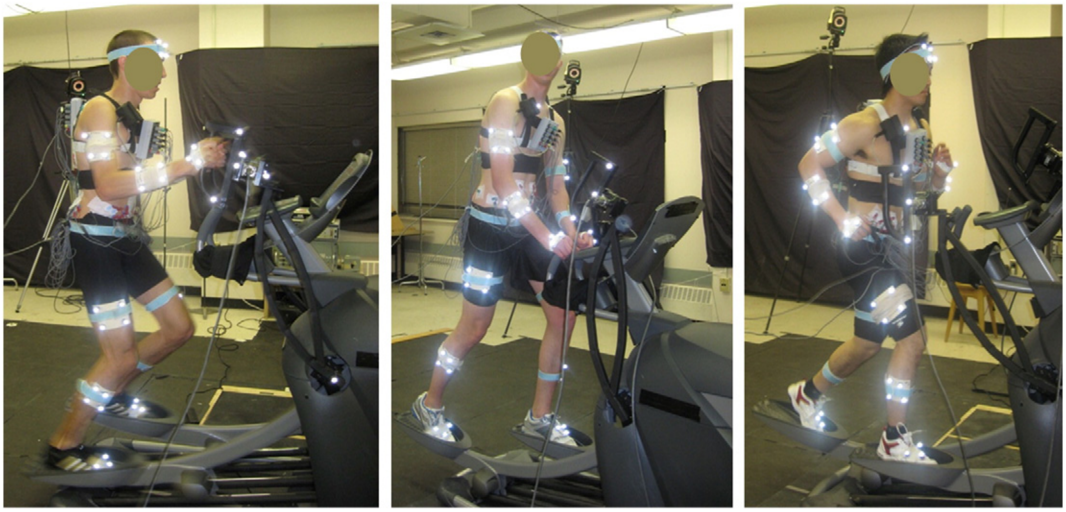

Fig. 1. Photographs of participants on the elliptical trainer in the three positions tested. Left to right, they include: using the handles, holding onto a central bar, and free-hand.

another without stopping in between, although participants were encouraged to alert us if they felt they were getting fatigued and then were allowed to rest until they felt ready to return to exercise. Order of collection was randomized for speed, stride length and hand position. Two collections were obtained for each combination of variables, with approximately 4 cycles of elliptical motion in each.

2.6. Kinematics

Motion data were processed using Visual 3D software (C-motion, Kingston, Ont, Canada). 3-dimensional lumbar angles were determined based on the angle between the T12 and sacral rigid bodies, thus representing the lumbar posture as the angle of the ribcage relative to the pelvis. These were carried out using a Visual 3D algorithm with a Cardan sequence of rotation (flexion/extension, side bending, followed by axial twist). Joint angles were filtered with a 6 Hz dual pass Butterworth filter. Signals were screened for abnormalities, processing errors, and marker movement error. Maximum and minimum joint angles were taken from the entire capture time, unless the signal drifted over time due to body position changes (i.e. neck flexion, which tended to increase lumbar flexion), in which case the max/min were extracted from a complete cycle deemed representative of the normal scope of motion. To calculate average joint positions for lumbar flexion angles, trials were clipped to ensure complete cycles of motion. Four angular outcomes were analyzed: 1) mean lumbar flexion angle: average lumbar sagittal position through one complete cycle; 2) total flexion/extension: angular change between maximum and minimum lumbar angles in the sagittal plane; 3) average total rotation: angular change between maximum and minimum (i.e. right and left) axial rotation; 4) average total side bending: angular change between maximum and minimum frontal position.

2.7. Statistical analysis

All analyses utilized the SPSS (version 17) package with a significance level chosen at $P<0.05$. Due to the highly symmetrical nature of the elliptical trainer, right/left symmetry was assumed, and the right side was used for analysis. For each of the 4 lumbar angles, (average lumbar flexion angle and total sagittal, frontal and axial motion) a $2\times2\times3$ repeated measures ANOVA was performed with speed, stride length and hand position as the independent variables. Bonferroni adjustments were used to account for multiple comparisons, resulting in a significance level of $P<0.0125$. A repeated measures one-way ANOVA with simple contrasts and Bonferroni adjustment was used to compare lumbar motion in walking with that elicited in the 12 elliptical conditions. The same process was used to compare peak EMG levels in walking with the 12 elliptical conditions, for each of the muscles being analyzed.

Pearson correlations were performed on lumbar angles elicited on the elliptical with those found in walking. For each of the 4 lumbar angles being analyzed, only the stride length/hand position/speed combination which resulted in the largest average angle was used for correlating. These data were similarly correlated with elliptical speed as well as the anthropometric variables of height, arm and leg lengths, arm and leg lengths normalized to body height, and available passive hip extension.

3. Results

Spine motion on the elliptical trainer is not the same as that produced when walking. In all variations of elliptical trainer use, participants adopted a posture of increased average forward flexion compared to walking: ranging from 8.8° (46/freehand/normal) to 12.3° (46/bars/fast) compared to 5.4° in walking (Fig. 2a). However, the total amount of sagittal motion utilized differed little from walking, with only two of the elliptical conditions (66/freehand/fast and 66/handles/fast) demonstrating a larger scope of flexion/extension than walking (Fig. 2c). Lumbar rotation was also greater on the elliptical in all but the 46/bars/normal condition (Fig. 2b). While walking averaged 14.8° of rotation, the elliptical elicited amounts varying from 16.6° (46/bars/normal) to 23.1° (66/handles/fast). The only direction in which more motion occurred during walking was the frontal plane, being significantly greater for walking in all but the two 66/freehand conditions (Fig. 2d). While the elliptical resulted in lumbar side bending averages between 8.0° and 11.0° (46/bars/normal and 66/freehand/fast, respectively), mean side bending when walking was 11.5°.

Pearson correlation analyses demonstrated a moderate relationship between lumbar motion that occurred when walking compared to that taking place on the elliptical, in all angles except side-bending (Table 1). This suggests that that rotation, flexion/extension and average forward lean demonstrated by participants in normal walking was moderately predictive of the same motion on the elliptical. Correlations between frontal motion in walking and the elliptical trainer were less than 0.17, thus poorly predictive (Table 1).

Speed when using the elliptical, stride length and hand position affected lumbar flexion angle and total spine motion about the three orthogonal axes of flexion/extension, lateral bend and twist. Specifically, increased speed resulted in more flexion/extension ($P<0.001$) and rotation ($P<0.001$) as well as a higher average lumbar flexion

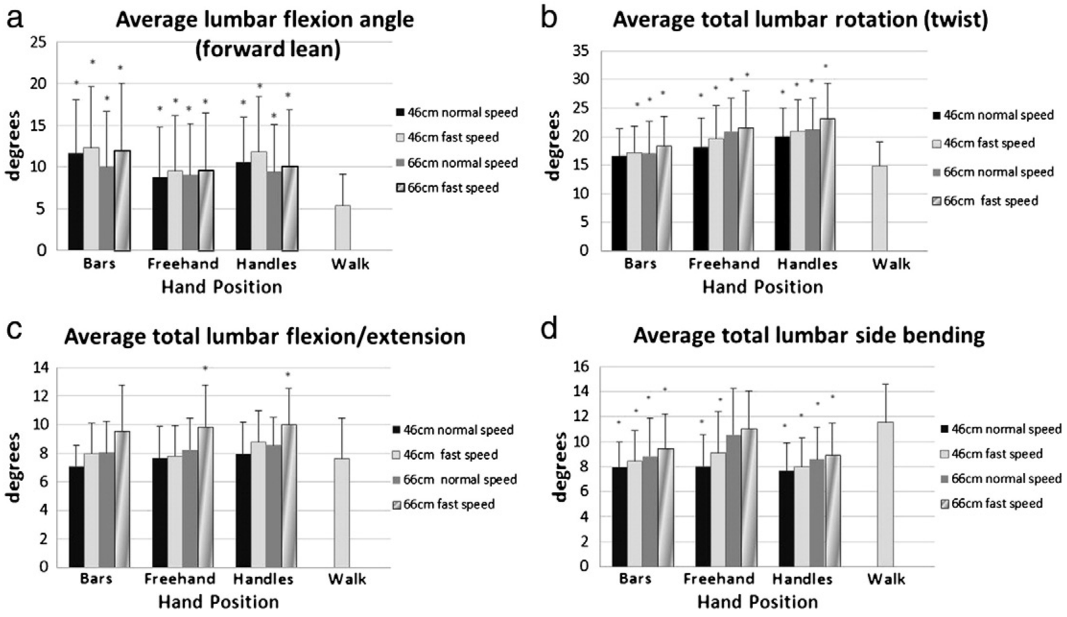

Fig. 2. Lumbar motion on the elliptical trainer with varying speeds, stride lengths, and hand positions is compared to lumbar motion during walking. * = significantly different than walking, $P<0.004$.

angle ($P=0.005$). Total lateral bend did not differ significantly with changes in speed ($P=0.074$) (Fig. 2). Increased stride length resulted in a corresponding increase in total spine motion in all 3 axes ($P<0.001$), but did not significantly affect average flexion angle ($P=0.070$) (Fig. 2). Hand position had a significant effect on average lumbar angle, lateral bend and rotation ($P=0.001$, $P<0.001$ and $P<0.001$, respectively), but the specifics varied with the axis: the greatest lumbar flexion angle was elicited when holding onto the bars, the least with freehand (Fig. 2a). Both total flexion/extension and lumbar rotation increased from bars to freehand to handles (Fig. 2b,c), but only significantly so with rotation ($P<0.001$). Freehand elliptical resulted in the most lateral bending, with use of the handles being the least (Fig. 2d).

Anthropometric characteristics affected forward trunk lean and lumbar twist magnitudes. Pearson correlations depicting these outcomes are shown in Table 2. On average, taller and long-legged participants utilized less lumbar rotation, but demonstrated a greater average flexion angle. For example, the tallest 8 participants averaged of 22.0(5)° of lumbar twist, compared to 28.1(6)° averaged over the shortest 8 participants (66/handles/fast condition). Similarly, these same 8 tall men averaged a forward lean angle of 18.4(8)° compared to 9.4(7)° in the shorter group (46/bars/normal condition). Measured hip extension also affected kinematics on the elliptical: the greater the hip extension the less lumbar rotation that occurred (hip extension is a negative number, thus a positive correlation indicates more hip extension is predictive of lower amounts of lumbar rotation). There were no significant correlations between anthropometrics and total lumbar lateral bend or total flexion/extension, nor were there any for normalized arm or leg lengths.

Peak trunk muscle activation for all muscles was generally greater when exercising on the elliptical trainer, with the significance level varying according to speed, hand position, and stride length (Table 3). The greatest difference was observed in the gluteal muscles, where average peak activations as high as 51% MVC occurred in Glut Med in the fast 66/freehand/fast condition, compared to 17% MVC in walking.

Table 1
Pearson correlations between mean lumbar motion occurring in walking and elliptical trainer use. W. = walking; 46BF = 46 cm/bars/fast condition; 66HF = 66 cm/handles/fast; 66FF = 66 cm/freehand/fast. Elliptical trials that demonstrated the greatest magnitude in each axis were chosen for comparisons. Bold/italics = significant at the $P<0.05$ level. See previous discussion for detailed definitions of the four lumbar angles: average flexion angle, and total flexion/extension, axial rotation, side bending.

	Avg L-fl angle		Total L-fl/ext		Total L-rot		Total L-side bend
	46BF	W.	66HF	W.	66HF	W.	66FF
W. Avg L-fl angle	**0.535**						
P-value	***0.015***						
66HF total L-fl/ext	0.206	0.113					
P-value	*0.222*	*0.505*					
W. total L-fl/ext	0.159	0.165	**0.363**				
P-value	*0.347*	*0.328*	***0.027***				
66HF total L-rot	0.098	0.282	**0.657**	0.302			
P-value	*0.571*	*0.096*	***0.001***	*0.074*			
W. total L-rot	0.106	**0.487**	0.235	**0.380**	**0.402**		
P-value	*0.537*	***0.003***	*0.168*	***0.022***	***0.015***		
66FF total L-side bend	0.176	0.013	0.314	0.054	0.236	−0.051	
P-value	*0.298*	*0.938*	*0.058*	*0.749*	*0.166*	*0.767*	
W. total L-side bend	0.092	0.047	0.022	**0.384**	0.094	0.321	0.174
P-value	*0.590*	*0.780*	*0.895*	***0.019***	*0.586*	*0.056*	*0.302*

Table 2
Pearson correlation results and significance levels: body anthropometrics and hip extension measurements were correlated with lumbar motion in 3 orthogonal axes as well as average forward lean on the elliptical trainer. *N* = normalized to body height. 66HF = 66 cm/handles/fast; 46BF = 46 cm/bars/fast; 66FF = 66 cm/freestyle/fast; Bold/italics = significance at the $P<0.05$ level.

	Arm length	*N* arm length	Leg length	*N* leg length	Height	Hip ext.
Tot. L-rotation	**−0.355**	0.060	**−0.384**	−0.100	**−0.460**	**0.374**
(66HF) *P*-value	***0.034***	*0.727*	***0.021***	*0.562*	***0.005***	***0.025***
Avg. L-flexion angle	0.220	0.158	**0.362**	0.162	**0.423**	0.189
(46BF) *P*-value	*0.190*	*0.349*	***0.028***	*0.339*	***0.009***	*0.263*
Avg. L-side bending	0.027	−0.022	0.049	−0.006	0.060	0.198
(66FF) *P*-value	*0.873*	*0.899*	*0.774*	*0.970*	*0.724*	*0.241*
Avg. L-flexion/ext.	−0.097	−0.018	−0.051	0.007	−0.088	0.066
(66HF) *P*-value	*0.568*	*0.916*	*0.765*	*0.969*	*0.603*	*0.698*

Table 3

Average peak activation levels (% MVC (SD)) of trunk and gluteal muscles when using the elliptical trainer compared to walking. Elliptical descriptions include stride length/hand configuration/speed. Bold indicates activation level significantly different from walking ($P<0.004$).

	RA	EO	IO	LD	T9ES	L4ES	GMed	GMax
Walking	3.6(3)	6.6(5)	13.0(8)	10.0(7)	7.2(5)	11.5(5)	17.1(8)	10.3(4)
46 cm/bars/normal	2.9(2)	5.8(3)	11.4(5)	**4.1(2)**	6.3(5)	14.3(5)	**27.9(14)**	**17.2(9)**
46 cm/bars/fast	3.9(3)	8.3(7)	15.7(8)	7.6(5)	10.0(7)	**16.4(8)**	**33.0(18)**	**24.9(12)**
66 cm/bars/normal	2.9(3)	5.8(4)	11.4(4)	9.1(6)	8.4(6)	17.8(7)	**26.9(11)**	**20.2(9)**
66 cm/bars/fast	5.0(6)	8.6(6)	17.2(8)	15.1(10)	13.2(9)	**20.6(7)**	**38.2(16)**	**28.9(11)**
46 cm/freehand/normal	4.0(4)	5.5(4)	12.0(5)	9.9(7)	8.1(6)	16.2(6)	**28.7(13)**	**17.8(7)**
46 cm/freehand/fast	5.9(7)	8.7(8)	15.8(7)	16.6(10)	**10.7(6)**	18.4(11)	**41.0(23)**	**28.8(12)**
66 cm/freehand/normal	3.0(2)	5.8(6)	12.8(7)	12.3(8)	9.9(9)	17.2(7)	**30.2(15)**	**20.5(10)**
66 cm/freehand/fast	6.0(6)	10.6(8)	**22.3(12)**	**17.8(9)**	**12.5(7)**	**22.7(8)**	**51.5(25)**	**32.5(13)**
46 cm/handles/normal	3.4(2)	5.4(4)	13.5(6)	7.8(6)	10.2(7)	15.3(5)	**29.1(14)**	**18.9(9)**
46 cm/handles/fast	5.0(4)	9.6(10)	**18.0(8)**	13.4(7)	12.5(7)	**18.2(7)**	**41.0(20)**	**30.6(14)**
66 cm/handles/normal	3.5(3)	5.1(4)	15.9(7)	11.1(9)	**14.6(9)**	**18.0(7)**	**32.0(15)**	**21.2(10)**
66 cm/handles/fast	6.5(8)	8.0(6)	**22.6(11)**	**19.9(10)**	**15.9(6)**	**20.2(6)**	**44.5(17)**	**32.3(14)**

4. Discussion

In this investigation, spine kinematics and muscle activation patterns utilized on the elliptical trainer were compared to those demonstrated in normal gait. The effect of hand position, stride length, and velocity on these elliptical outcome measures was analyzed, as were correlations between anthropometric measures and resulting spine kinematics.

Although the elliptical trainer tends to constrain lumbar lateral bend, both lumbar rotation and forward flexion angles were greatly increased on the elliptical when compared to walking (Fig. 2), thus the first hypothesis applies for these three axes of motion. Repetitive flexion and axial rotation are known to be causative of lumbar disc degeneration and annular delamination (Callaghan and McGill, 2001; Drake and Callaghan, 2009; Drake et al., 2005; Marshall and McGill, 2010). Given that the participants in this study averaged a cadence of 53(7) cpm or 69(9) cpm at the faster speed, the total number of spine flexion/rotation events in a half hour session could be 3180–4140, and considerably higher in those exercising at a faster than average rate. The scope of axial rotation utilized on the elliptical when using the handles averaged 23°; almost identical to the 24° described in running (Schache et al., 2003) but with an increased lumbar flexion angle, which differs from the generally extended position of the spine and anterior pelvic tilt in running (Franz et al., 2009; Schache et al., 2003). Thus, the elliptical causes the spine to rotate through most of its available range of axial rotation but in an associated position of lumbar flexion, which may be problematic for individuals who are intolerant of repetitive flexion/rotation of the spine, such as those with lumbar discogenic disorders (McGill, 2002).

Hand position, stride length and velocity all had significant effects on lumbar spine kinematics (Fig. 2), thus confirming the second hypothesis. Specifically, those people with flexion intolerance would be encouraged to avoid holding onto the central bar for support, as it encourages a more flexed posture of the lumbar spine. However, it also demands the least lumbar twist, which may be advantageous for others. Increasing speed and stride length will, in general, produce the largest amount of spine rotation and flexion/extension, thus should be used with caution. Of interest, use of the elliptical in a 66/handles/fast condition resulted in average total lumbar rotation of 23.2°, yet voluntary active lumbar rotation in upright stance has been shown to average 23.9° (Moreside, 2010). Lumbar flexion associated with this twist is greater on the elliptical, however, allowing opening of the facet joints and lessening the rotational compressive forces on these joints, albeit perhaps at the cost of increased annular stresses. A person's height, arm and leg length may affect lumbar motion on the elliptical trainer in a group of young adult males, as was suggested in hypothesis 3. Despite the ability to vary stride length and hand position, there is no ability to raise or lower the handles or bars. Consequently, taller people may tend to flex more, yet rotate less, while the shorter people will do the opposite: adopt a more upright stance but rotate more around the vertical axis (Table 2). One participant of interest, who regularly participated in power lifting and weight training activities, demonstrated lumbar rotation values on the elliptical trainer of approximately 23° to each side, with a resulting 46° of total lumbar rotation in the 66/handles/fast condition, while the group average was only 23.1 (6)°. Despite being only 172 cm in height (mean group height was 178 (7) cm), he had a greater than average forward lean angle in 11 of the 12 elliptical conditions. Further investigation revealed that this participant also demonstrated a marked lack of hip mobility: 42° and 45° of total hip rotation (the sum of internal and external rotation) for the right and left leg, respectively; small when compared to published 50th percentile values of 59° (Moreside and McGill, 2011). Consequently, he may have adopted this motor pattern of lumbar rotation and flexion to compensate for lack of hip rotation. Indeed, his walking lumbar total rotation values averaged 30°, compared to a group average of 14.8°, thus affirming the significant correlation between rotation in walking and that on the elliptical (Table 1). One cannot ignore the effect of sport-specific training on spine kinematics, either. Although not addressed in this study, there did appear to be a trend for men who were highly trained in body contact sports, such as American football defensive players, to adopt a more flexed posture under activity, while those who specialized in running (distance or sprint) were likely to be more upright. Such observations should be considered when determining the appropriateness of the elliptical trainer for specific rehabilitation or fitness protocols.

Muscle activation patterns on the elliptical trainer are generally higher than those found in walking (Table 3), with the greatest differences demonstrated by the back and hip extensor groups. The increased forward flexion angle adopted on the elliptical would require little change in the activation of the abdominal muscles, although IO and LD activity increased at the higher speeds when the participants were using the handles or exercising freehand. Likely, as velocity requirements increased, the IO and LD muscles became more active either to drive the elliptical velocity via the handles or stabilize the torso against the increasingly large torsion associated with these conditions (Fig. 2b). Greater activation of the ES muscles on the elliptical trainer is in keeping with the associated increase in lumbar flexion angle (Fig. 2a) and lumbar moment (Leteneur et al., 2009). However, the lack of significance for changes in T9ES activation when holding onto the bars (the condition producing the largest average lumbar flexion angle) suggests that the participants tended to lean on the stationary bar, thus reducing their lumbar flexion moment and reducing the need for thoracic extensor activity. Increased spine and hip flexion angles on the elliptical trainer (Burnfield et al., 2010) would necessitate greater activity of the hip extensor/abductor muscle groups, as shown by the large increases in Glut Med and Max activity. The 51.5%MVC, averaged by Glut Med during the 66/

freehand/fast condition, is of a magnitude similar to specific hip abduction exercises in the literature: activation levels of 56% MVC and 46% MVC for weight bearing hip abduction exercises performed in single leg stance have been described (Bolgla and Uhl, 2005). Given that exercising on the elliptical trainer for 20 min would result in approximately 1060 repetitions of each leg (using the self-selected average of 53 cps), it appears to offer an enhanced challenge to the gluteal muscles, especially when using the longer stride lengths, or increasing the speed (Table 3).

This study agrees with those of Burnfield et al. (2010) and Lu et al. (2008) who describe increased spinal flexion on the elliptical compared to walking. Both of these studies did not address different hand positions, speeds or stride lengths, as the focus of both studies was on the lower extremities more so than the trunk. This may explain why Burnfield et al. (2010) did not find a significant difference in Glut Med activity between walking and the elliptical, as our findings were that, although Glut Med activity was greater in all conditions on the elliptical, it was greatest when the handles were not used, and stride length and speed were at their highest (Table 3). The magnitudes of GMax and GMed activity when walking were also higher in the work of Burnfield et al. (2010): 26% and 38% MVC, respectively (Burnfield et al., 2010), compared to the present findings of 10% and 17% MVC, which may possibly be explained by different methods for quantifying MVCs or that the average age of their participants was 48(23) yrs compared to 23(3) yrs in the current study. In addition, their participant base was 50% females compared to our all male population, which might explain their slightly shorter stride length (71 cm) and higher velocity (54 cpm) when walking (Crosbie et al., 1997; Schache et al., 2003).

This study was limited to young, fit males, as it was part of a larger study that necessitated a younger group to reduce the likelihood of arthritic changes. Females were excluded to reduce the number of variables. Future studies should expand this information to include both sexes of varying ages. The results of this study represent the findings on only one type of elliptical trainer. There are many models available that may result in slightly different postures, and some with varying incline abilities. It was felt that variable stride length was an important feature to study, thus this specific model was chosen. Extrapolating these results to all models should be done with caution.

Exercising on the elliptical trainer is different from walking. Its effect on lumbar spine kinematics varies according to hand position, speed and stride lengths. Lumbar rotation and average flexion angle are generally higher on the elliptical trainer, thus it may not be the equipment of choice for those with flexion/rotation intolerant spines. While holding onto a central stationary bar reduces lumbar rotation, it will also increase the average flexion angle, which may be advantageous for those with extension intolerance. Thus, there is no absolute doctrine as to whether or not the elliptical trainer will be injurious to the lumbar spine: recommendations need to be chosen on a case by case basis, taking into consideration any underlying spine pathologies, then recommending appropriate velocity, stride length and hand position modulators. It remains an excellent tool for encouraging gluteal activity.

Conflict of interest statement

The authors have no conflicts of interest in the preparation or submission of this manuscript.

Acknowledgments

This work was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

Adams, M.A., Hutton, W.C., 1980. The effect of posture on the role of the apophyseal joints in resisting intervertebral compressive forces. J. Bone Joint Surg. Br. 62B, 358–362.

Adams, M.A., Hutton, W.C., 1981. The relevance of torsion to the mechanical derangement of the lumbar spine. Spine 6, 241–248.

Aultman, C.D., Scannell, J., McGill, S.M., 2005. The direction of progressive herniation in porcine spine motion segments is influenced by the orientation of the bending axis. Clin. Biomech. 20, 126–129.

Bolgla, L.A., Uhl, T.L., 2005. Electromyographic analysis of hip rehabilitation exercises in a group of healthy subjects. J. Orthop. Sports Phys. Ther. 35, 487–494.

Brereton, L.C., McGill, S.M., 1998. Frequency response of spine extensors during rapid isometric contractions: effects of muscle length and tension. J. Electromyogr. Kinesiol. 8, 227–232.

Burnfield, J.M., Shu, Y., Buster, T., Taylor, A., 2010. Similarity of joint kinematics and muscle demands between elliptical training and walking: implications for practice. Phys. Ther. 90, 1–17.

Callaghan, J.P., McGill, S.M., 2001. Intervertebral disc herniation: studies on a porcine model exposed to highly repetitive flexion/extension motion with compressive force. Clin. Biomech. 16, 28–37.

Callaghan, J.P., Patla, A.E., McGill, S., 1999. Low back three-dimensional joint forces, kinematics and kinetics during walking. Clin. Biomech. 14, 203–216.

Cholewicki, J., McGill, S., Norman, R.W., 1995. Comparison of muscle forces and joint load from an optimization and EMG assisted lumbar spine model: towards development of a hybrid approach. J. Biomech. 28, 321–331.

Crosbie, J., Vachalathiti, R., Smith, R., 1997. Age, gender and speed effects on spinal kinematics during walking. Gait Posture 5, 13–20.

Drake, J.D., Callaghan, J.P., 2009. Intervertebral neural foramina deformation due to two types of repetitive combined loading. Clin. Biomech. 24, 1–6.

Drake, J.D., Aultman, C.D., McGill, S.M., Callaghan, J.P., 2005. The influence of static axial torque in combined loading on intervertebral joint failure mechanics using a porcine model. Clin. Biomech. 20, 1038–1045.

Franz, J.R., Paylo, K.W., Dicharry, J., Riley, P.O., Kerrigan, D.C., 2009. Changes in the coordination of hip and pelvis kinematics with mode of locomotion. Gait Posture 29, 494–498.

Gordon, S.J., Yang, K.H., Mayer, P.J., Mace Jr., A.H., Kish, V.L., Radin, E.L., 1991. Mechanism of disc rupture. A preliminary report. Spine (Phila Pa 1976) 16, 450–456.

Granata, K.P., Marras, W.S., 1993. An EMG assisted model of loads on the lumbar spine during asymmetric trunk extensions. J. Biomech. 26, 1429–1438.

Granata, K.P., W.S., M., 2000. Cost–benefit of muscle cocontraction in protecting against spinal instability. Spine 25.

Gunning, J.L., Callaghan, J.P., McGill, S.M., 2001. Spinal posture and prior loading history modulate compressive strength and type of failure in the spine: a biomechanical study using a porcine cervical spine model. Clin. Biomech. 16, 471–480.

Leteneur, S., Gillet, C., Sadeghi, H., Allard, P., Barbier, F., 2009. Effect of trunk inclination on lower limb joint and lumbar moments in able men during the stance phase of gait. Clin. Biomech. 24, 190–195.

Lu, D., Le, P., Davidson, B., Zhou, B.H., Lu, Y., Patel, V., et al., 2008. Frequency of cyclic lumbar loading is a risk factor for cumulative trauma disorder. Muscle Nerve 38, 867–874.

Marshall, L.W., McGill, S.M., 2010. The role of axial torque in disc herniation. Clin. Biomech. 25, 6–9.

McGill, S.M., 2002. Low Back Disorders. Human Kinetics, Champaign.

Mier, C.M., Feito, Y., 2006. Metabolic cost of stride rate, resistance, and combined use of arms and legs on the elliptical trainer. Res. Q. Exerc. Sport 77, 507–513.

Moreside, J.M., 2010. The effect of limited hip mobility on the lumbar spine in a young adult population. PhD dissertation, University of Waterloo, Canada.

Moreside, J.M., McGill, S.M., 2011. Quantifying normal 3D hip ROM in healthy young adult males with clinical and laboratory tools: hip mobility restrictions appear to be plane-specific. Clin. Biomech. 26, 824–829.

Moreside, J.M., Vera-Garcia, F.J., McGill, S.M., 2007. Trunk muscle activation patterns, lumbar compressive forces, and spine stability when using the Bodyblade. Phys. Ther. 87, 153–163.

Nachemson, A.L., Morris, J.M., 1964. In vivo measurements of intradiscal pressure. J. Bone Joint Surg. Br. 46A, 1077–1092.

Punnett, L., Fine, L.J., Keyserling, W.M., Herrin, G.D., Chaffin, D.B., 1991. Back disorders and nonneutral trunk postures of automobile assembly workers. Scand. J. Work Environ. Health 17, 337–346.

Schache, A.G., Blanch, P.D., Rath, D.A., Wrigley, T., Bennell, K.L., 2003. Differences between the sexes in the three-dimensional angular rotations of the lumbo-pelvic-hip complex during treadmill running. J. Sports Sci. 21, 105–118.

Vera-Garcia, F.J., Brown, S.H., Gray, J.R., McGill, S.M., 2006. Effects of different levels of torso coactivation on trunk muscular and kinematic responses to posteriorly applied sudden loads. Clin. Biomech. 21, 443–455.

Vera-Garcia, F.J., Moreside, J.M., McGill, S.M., 2010. MVC techniques to normalize trunk muscle EMG in healthy women. J. Electromyogr. Kinesiol. 20, 10–16.