11-2013

Lower Extremity Kinematics During Walking and Elliptical Training in Individuals With and Without Traumatic Brain Injury

Thad Buster
Madonna Rehabilitation Hospital

Judith Burnfield
Madonna Rehabilitation Hospital

Adam P. Taylor
Madonna Rehabilitation Hospital

Nikolaos Stergiou
University of Nebraska at Omaha, nstergiou@unomaha.edu

Lower Extremity Kinematics During Walking and Elliptical Training in Individuals With and Without Traumatic Brain Injury

Thad Buster, MS, Judith Burnfield, PT, PhD, Adam P. Taylor, BS, and Nicholas Stergiou, PhD

Background and Purpose: Elliptical training may be an option for practicing walking-like activity for individuals with traumatic brain injuries (TBI). Understanding similarities and differences between participants with TBI and neurologically healthy individuals during elliptical trainer use and walking may help guide clinical applications incorporating elliptical trainers.

Methods: Ten participants with TBI and a comparison group of 10 neurologically healthy participants underwent 2 familiarization sessions and 1 data collection session. Kinematic data were collected as participants walked on a treadmill or on an elliptical trainer. Gait-related measures, including coefficient of multiple correlations (a measure of similarity between ensemble joint movement profiles; coefficient of multiple correlations [CMCs]), critical event joint angles, variability of peak critical event joint angles (standard deviations [SDs]) of peak critical event joint angles, and maximum Lyapunov exponents (a measure of the organization of the variability [LyEs]) were compared between groups and conditions.

Results: Coefficient of multiple correlations values comparing the similarity in ensemble motion profiles between the TBI and comparison participants exceeded 0.85 for the hip, knee, and ankle joints. The only critical event joint angle that differed significantly between participants with TBI and comparison participants was the ankle during terminal stance. Variability was higher for the TBI group (6 of 11 comparisons significant) compared with comparison participants. Hip and knee joint movement patterns of both participants with TBI and comparison participants on the elliptical trainer were similar to walking (CMCs $\geq$ 0.87). Variability was higher during elliptical trainer usage compared with walking (5 of 11 comparisons significant). Hip LyEs were higher during treadmill walking. Ankle LyEs were greater during elliptical trainer usage.

Discussion and Conclusions: Movement patterns of participants with TBI were similar to, but more variable than, those of comparison participants while using both the treadmill and the elliptical trainer. If incorporation of complex movements similar to walking is a goal of rehabilitation, elliptical training is a reasonable alternative to treadmill-based training.

Video Abstract available (see Video, Supplemental Digital Content 1, http://links.lww.com/JNPT/A65) for more insights from the authors.

Key words: *gait, locomotor training, nonlinear, physical rehabilitation, variability*

Movement and Neurosciences Center, Institute for Rehabilitation Science and Engineering, Madonna Rehabilitation Hospital, Lincoln, Nebraska (T.W.B, J.M.B, A.P.T.); and Nebraska Biomechanics Core Facility, University of Nebraska Omaha (T.W.B, N.S.)

This study was funded, in part, by The Bill Kubly student research scholarship grant awarded to Thad W. Buster. For the remaining authors, none were declared.

Supplemental digital content is available for this article. Direct URL citation appears in the printed text and is provided in the HTML and PDF versions of this article on the journal's Web site (www.jnpt.org).

Correspondence: Thad Buster, MS, Institute for Rehabilitation Science and Engineering, Madonna Rehabilitation Hospital, 5401 South St, Lincoln, NE 68506 (tbuster@madonna.org).

INTRODUCTION

Approximately 80,000 to 90,000 new traumatic brain injuries (TBI) occur annually that result in long-term disability.[1] Walking difficulties are common following TBI due to motor, sensory, and cognitive deficits.[2-5] With rehabilitation, up to 73% of individuals with TBI can achieve independent ambulation within 5 months of their injury.[6,7] However, a majority of people with severe TBI experience persistent long-term challenges.[8] Therefore, identifying training activities that could be used to continue rehabilitation and improve gait once formal therapy has ended would help address the needs of those still attempting to recover skills. Unfortunately, no clear recommendations exist for TBI rehabilitation following discharge.

Task-specific rehabilitation has been encouraged as a means of promoting beneficial neuroplastic changes and improving functional outcomes in those with neurologic injury.[9] One area of intensive focus over the past 2 decades has been the use of treadmill training as a means of promoting intensive practice for over ground gait. Unfortunately, some individuals with physical disabilities lack the strength and movement control abilities to sustain repetitive stepping on a treadmill without assistance.

Documented similarities in lower extremity joint motions and muscle demands between walking and elliptical training in individuals without disability[10] suggest that elliptical trainers may provide an alternative approach for task-related training. Elliptical trainers have mechanical linkages between the reciprocating arm handles and the foot pedals, which provides a means for individuals with lower limb weakness to help advance their own legs. In addition, the sustained double-limb support may be helpful for those with balance deficits. These attributes could be the reason that elliptical trainers have served as an effective tool for improving functional mobility and gait in individuals with multiple sclerosis and stroke.[11-13] However, given the lack of existing research, it is unclear whether movements generated while training on an elliptical device display similarities (task-relatedness) to walking in those recovering from a severe TBI.

Beyond providing activities that approximate the normal kinematics of walking, promoting movement variability has been encouraged as a means of facilitating a healthy and highly adaptable motor recovery.[14] Momentum for this concept has increased as clinicians realize that both amount (ie, standard deviation [SD]) and temporal structure (ie, Lyapunov Exponent [LyE]) of variability provide valuable complementary information and can guide clinical decision making.[15] Importantly, it has been proposed that movements that lack variability and instead exhibit very repetitive and stereotypical behavior over time are not beneficial and they are indicative of pathology. On the contrary, movements that present with too much variability, exhibiting disorganization and increased randomness are also not beneficial and indicative of pathology.[16] Therefore, it seems that there is an optimal state of variability that is desirable and effective for health; however, little is known regarding the variability allowed by elliptical trainers and how this may be altered in individuals with TBI. Therefore, the investigation of variability can be used to explore new interventions (eg, training on elliptical devices, herein referred to as "elliptical training") to maximize healthy and adaptable motor learning.[16]

The purpose of this study was to compare lower extremity movements and their variability between participants with TBI and healthy matched comparison participants, and also make comparisons between walking and elliptical training. We hypothesized that the overall motion profiles and peak critical joint angles of participants with TBI would differ from comparison participants during the activities studied. In addition, we hypothesized that participants with TBI would display greater movement variability (ie, higher SDs) of critical event joint angles and more disorganization in the structure of variability over time (ie, higher maximum LyE) as compared to comparison participants due to weakness, spasticity, and loss of motor control. On the basis of our previous research, we also hypothesized that motion patterns at the hip and knee would demonstrate strong similarities between walking and elliptical training, yet the ankle would not.[10] Finally, we hypothesized that there would be decreased hip, knee, and ankle variability (ie, lower SD) for critical event joint angles and more stereotypical and rigid structure of variability over time (ie, lower maximum LyE), indicating less divergence in the movement trajectories during elliptical training compared with walking.

METHODS

Participants

Ten adults with chronic severe TBI were recruited from the Lincoln, Nebraska community. Inclusion criteria for participation included initial loss of consciousness greater than 6 hours[17]; currently 5 or more on the Functional Independence Measure (FIM) locomotor walk subscore,[18] and currently 6 or more on the Rancho level of cognitive function. Ten gender-, height-, mass-, and age-matched comparison participants also were recruited. All participants were free of orthopedic and cardiovascular disease (Table 1).

Table 1. Participant Anthropometrics and Between-Group Comparison of Dynamic Gait Index, Berg Balance, Proprio 4000 Dynamic Motion Analysis, Manual Muscle Test Grades for Knee Extensors, and Ankle Plantar Flexors, Ankle EMG Response Following Quick-Stretch of Gastrocnemius (G) and Tibialis Anterior

	Participant Anthropometrics and Clinical Measures X (SD)	
	Comparison Participants (n = 10)	**Participants With TBI (n = 10)**
Age, y	34 (13)	36 (13)
Height, cm	174 (10)	172 (10)
Weight, kg	74 (14)	70 (16)
LOC, d	NA	23 (23)
Time since injury, y	NA	10 (6)
FIM locomotor (score)	7 (0)	6.7 (0.5)
Dynamic Gait Index (score)	24 (0)[b]	20 (4)[b]
Berg Balance (score)	56 (0)[b]	53 (6)[b]
Dynamic posturography (DMA score)	123 (31)[c]	349 (300)[c]
Left Knee Extensors MMT (Grade)	5 (0.5)	4 (0.5)
Right Knee Extensors MMT (Grade)	5 (0.5)	4 (0.5)
Left heel raises (#)	24 (2.8)	21 (7.8)
Right heel raises (#)	25 (0.0)[d]	20 (8.0)[d]
Left ankle EMG QS (participants with sustained response)	NA	G (n = 2)
Right ankle EMG QS (participants with sustained response)	NA	G (n = 3); TA (n = 1)[a]

Abbreviations: DMA, Dynamic Motion Analysis; EMG, electromyographic; FIM, Functional Independence Measure; KE, Knee Extensors; LOC, loss of consciousness; MMT, Manual Muscle Test; NA, not applicable; QS, Quick-Stretch; TA, tibialis anterior.

[a]EMG activity recorded post quick-stretch exceeding > 500 ms in duration.

[b]Traumatic brain injury (TBI) displayed significantly poorer performance than control group ($P = 0.015$).

[c]TBI displayed significantly poorer balance than control group ($P = 0.002$).

[d]TBI displayed significantly weaker right plantar flexors than control group ($P = 0.015$).

Instrumentation

The elliptical trainer (TSXa, True Fitness Technology, St Louis, Missouri) used in this study was selected in part because it promoted movement patterns similar to gait in healthy comparison participants.[10] The elliptical trainer was equipped with both static and moving handles. Walking was performed on a treadmill (95Ti, Life Fitness Corp, Schiller Park, Illinois). Both the elliptical trainer and treadmill were equipped with horizontal handrails. The elliptical trainer also had handles linked to and moving reciprocally with the foot pedals. Electromyographic (EMG) signals and foot-treadmill contact patterns were recorded (1200 Hz; MA-300-10; Motion Lab Systems Inc, Baton Rouge, Louisiana) using surface electrodes (MA-411; Motion Lab Systems Inc) and footswitch insoles (B & L Engineering, Santa Ana, California), respectively. A motion capture system (Qualisys AB, Gothenburg, Sweden) defined 3-dimensional motion of participants' lower extremities and the pedals of the elliptical trainer. Motion data were sampled (120 Hz) and recorded on a computer interfaced with Qualisys Track Manager software (Qualisys AB). Subsequent signal processing was performed using Visual 3D (C-Motion, Germantown, Maryland) and Chaos Data Analyzer professional version software (Physics Academic Software, North Carolina State University, Raleigh). Computerized dynamic posturography (Proprio 4000, Perry Dynamics, Decatur, Illinois) was used to assess balance. This system includes a 28-inch computer-controlled multidirectional platform capable of 14° of lateral, anterior, and posterior tilt at 0° to 60° per second. Motion data were sampled (4 Hz) using the system's ultrasound sensors. To ensure safety, all participants wore a fall arresting harness (SafeLight Universal 3M 10910, St Paul, Minnesota) during walking, elliptical training, and posturography assessments; however, body weight was not supported.

Procedures

All testing occurred in the Movement and Neurosciences Center at Madonna Rehabilitation Hospital. After signing an informed consent approved by Madonna Rehabilitation Hospital's institutional review board, each volunteer participated in 3 sessions. During the first 2 sessions, participants were familiarized with exercise equipment and procedures. To ensure variability, measures were not influenced by imposition of machine settings outside of participants' comfort zones, participants self-selected their settings on both devices. Specifically, on the treadmill, investigators started the treadmill at the lowest-speed setting available. The speed was gradually increased until participants indicated that they were at their comfortable speed. Once confirmed, the participants were asked to walk for up to 3 minutes. Similarly, on the elliptical trainer, investigators started the machine at the lowest stride length available. The stride length was then incrementally adjusted until participants indicated that they were at a comfortable stride length. Once stride length was determined, participants were instructed to propel the machine at a comfortable speed for up to 3 minutes.

While using the treadmill and elliptical trainer, participants in the TBI group chose to hold the horizontal handrails for comfort or safety. Therefore, their comparison group counterparts were required to hold the handrails in the same manner as their TBI participant predecessors. Conditions were randomized (MATLAB, Mathworks Inc, Sherborn, Massachusetts). Participants returned for a second, identically structured, familiarization session spaced at least 24 hours later, but not more than 72 hours after the first session.

Because of the heterogenous nature of residual deficits associated with TBI, participants performed clinical assessments during the third session to assist with describing the functional status of the individuals participating in this study. Specifically, participants completed the Berg Balance Test and the Dynamic Gait Index.[19] In addition, because of the anticipated ceiling effect of the Berg Balance and Dynamic gait index for those with only minimal to moderate balance deficits,[20] participants performed 3 computerized posturography tests (ie, Proprio 4000 pre-programmed PROPRIO Tests [Perry Dynamics]) to further assess balance. Each test lasted 120 seconds or until the ultrasound-tracking sensor, placed between participant's posterior superior iliac spines, moved greater than 3 inches in the anterior-posterior, medial-lateral, or vertical plane. Participants rested up to 5 minutes between each test, and Dynamic Movement Analysis scores were recorded from the system following each test. The Dynamic Movement Analysis score represents the summation of anterior-posterior, medial-lateral, and vertical inches of movement (ie, the difference between the sensors current position and the last position) recorded by the ultrasound sensor of the motion capture system throughout the 120-second test. The system calculates an adjusted score for those who are unable to complete the full 2 minutes by adding 12 points for every second remaining in the test. The theoretical minimum and maximum scores possible for the test are 0 and 1440, respectively. Higher dynamic movement analysis scores indicate poorer balance, while lower scores reflect better balance. Lower extremity muscle strength was assessed using standard manual muscle testing procedures.[21] Supplementary EMG signals were collected using surface electrodes placed bilaterally over the vastus lateralis, medial hamstrings, gastrocnemius, and tibialis anterior to assess the response to quick stretch tests. Specifically, surface EMG signals were collected for 5 seconds following the application of a quick stretch that moved the joint through the full range of motion. Electromyographic signals that demonstrate sustained response are highly correlated with higher scores on the Modified Ashworth Scale.[22]

After clinical testing, compression closing footswitch insoles were placed inside the shoes. Reflective markers were placed bilaterally over the iliac crest, posterior superior iliac spine, anterior superior iliac spine, greater trochanter, medial and lateral femoral condyles, medial and lateral malleoli, posterior heel, medial first metatarsal, between the distal second and third metatarsals, and over the distal lateral fifth metatarsal and lateral border of the mid-foot. Tracking marker clusters were secured on the trunk, thigh, and lower leg.

After recording a static calibration trial to define the lower extremity biomechanical model, participants walked and performed elliptical training in a random order, using procedures identical to those described for the familiarization sessions. In particular, participants trained for up to 3 minutes once adjustments for speed and stride length were complete. Because of fatigue, one participant only completed 1 minute at her self-selected settings, which was still sufficient to collect 30 continuous strides.

Data Analysis

Total scores were calculated for the Dynamic Gait Index and Berg Balance Tests. Dynamic Movement Analysis scores from 3 trials were averaged for each participant. Electromyographic data were processed according to those described by Cooper et al[22] and visually inspected to determine duration of muscle response to quick stretch. Electromyographic signals that exceeded the baseline for durations greater than 500 ms following quick stretch applications were considered a sustained response.[22]

Thirty strides of unfiltered data for walking and elliptical training recorded during the final minute were used to calculate stride characteristics and lower extremity sagittal plane kinematics. Thirty continuous strides have previously been described as sufficient for the nonlinear tools utilized in this study.[23,24] Footswitches defined 8 gait cycle phases for walking.[25] During elliptical training, the pedal arm of the elliptical trainer defined movement cycle phasing.[10]

Data were exported and processed in Visual 3D software (C-Motion). Hip, knee, and ankle joint angles were calculated for each percentage of the time normalized gait cycles, defined as initial contact of the dominant foot to the next ipsilateral contact. For each activity, joint angles associated with critical events during gait at the hip, knee, and ankle were identified.[25] The temporal structure of variability during walking and elliptical training was evaluated with the maximum LyE. This parameter represents the closeness of the overlap of movement trajectories in consecutive movement cycles, by calculating the exponential separation of nearby trajectories in a reconstructed state space of a joint angle time series.[26] Separated points diverge rapidly and represent instability. Stereotypical systems with little or no divergence in the movement trajectories have maximum LyE values near zero. Systems that exhibit disorganization and randomness have a large amount of divergence in the movement trajectories (LyE values > 0.5),[27] while LyE values of human lower extremity joint angles during gait are close to 0.1.[28] The values depend on the algorithms used to calculate the LyE and the associated software. In this study, we used the global false nearest neighbors' algorithm to determine that the appropriate minimum embedded dimensions were 5. This default parameter was subsequently used when calculating LyE for all trials in Chaos Data Analyzer software package (Physics Academic Software). This software package utilizes the Wolf et al[29] algorithm for the calculation of the LyE, which has been found more robust for small time series such as those we used in this study.

During walking, average speed, stride length, and cadence were determined for each stride using Visual 3D algorithms. During elliptical training, stride length was recorded from the console and later confirmed by 3-dimensional pedal motion trajectories. Elliptical training speed and cadence were calculated using Visual 3D.

Statistical Analysis

Descriptive statistics were performed on all key variables. Independent *t* tests were performed to evaluate differences in gait and balance measures (ie, Dynamic Gait Index, Berg Balance Test, Dynamic Movement Analysis scores) between groups. For stride characteristics (ie, speed, cadence, and stride length), a balanced multivariate analysis of variance, using a general linear model, was used to model the main effects of Group (TBI vs comparison group) and Condition (treadmill walking vs elliptical training) and their interaction. Coefficient of multiple correlations (CMC) assessed overall similarities in ensemble joint movement profiles at the hip, knee, and ankle between (1) walking and elliptical training for each group and (2) the control and TBI groups for both walking and elliptical training. Coefficient of multiple correlations values close to 1.0 indicate strong similarity between ensemble profiles being compared. In contrast, values approximating zero indicate no similarity.[30] Separate analyses of variance (2×2 ANOVAs) with repeated measures identified differences in critical event joint angles, SDs of critical event joint angles, and LyE, at the hip, knee, and ankle between group (control and TBI) and conditions (elliptical training and treadmill walking) and their interactions. Before performing the ANOVAs, the data were screened for normality using the Shapiro-Wilk test. If normality assumptions were violated, the data were transformed into ranks and the ANOVAs were calculated using the ranked data.

RESULTS

Participant-specific data for select clinical measures are summarized in Table 1. Participants with TBI scored more poorly than comparison participants for Dynamic Gait Index ($P = 0.015$), Berg Balance test ($P = 0.015$), and Dynamic Movement Analysis scores ($P = 0.002$). In participants with TBI, right plantar flexor manual muscle test grade was weaker than that in comparison participants ($P = 0.015$). In addition, 4 of 10 participants with TBI had documented ankle muscle activity that persisted (ie, either clonically or continuously) for longer than 500 ms following the application of a quick stretch.

Stride characteristics for each group during walking and elliptical training are highlighted in Table 2. There were no significant differences between participants with TBI and comparison participants ($P = 0.081$), treadmill walking and elliptical trainer usage ($P = 0.140$), or for the interaction effect between groups and conditions ($P = 0.280$).

TBI Versus Comparison Group

Motion Profile Similarities

The motion profiles of participants with TBI and comparison groups during walking were very similar at the hip, knee, and ankle. All CMC values were at least 0.89. Similarly, in both groups motion profiles during elliptical training were highly correlated at the hip, knee, and ankle with all CMC values exceeding 0.85 (Table 3 and Figures 1A, B, and C).

Table 2. Comparison of Select Stride Characteristics Between Participants With TBI (n = 10) and Comparison Participants (n = 10) and Between Walking and Elliptical

	Stride Characteristics X (SD)			
	Participants With TBI		Comparison Participants	
Variable	Walking	Elliptical	Walking	Elliptical
Speed, m/s	0.93 (0.21)	0.77 (0.29)	0.93 (0.25)	0.89 (0.22)
Cadence, steps/min	91 (18)	84 (24)	99 (7)	98 (17)
Stride length, m	1.2 (0.2)	1.1 (0.2)	1.1 (0.2)	1.1 (0.1)

Abbreviation: TBI, traumatic brain injury.

Table 3. Hip, Knee, and Ankle CMC Values for Participants With TBI (n = 10) and Comparison Participants (n = 10)

	X (SD) CMC Values			
Joint	Participants With TBI Walking vs Elliptical	Comparison Participants Walking vs Elliptical	Walking TBI vs Comparison Participants	Elliptical TBI vs Comparison Participants
Hip	0.89 (0.04)	0.87 (0.04)	0.94 (0.06)	0.98 (0.03)
Knee	0.88 (0.04)	0.88 (0.03)	0.96 (0.03)	0.98 (0.02)
Ankle	0.57 (0.09)	0.54 (0.07)	0.89 (0.07)	0.85 (0.14)

Abbreviations: CMC, coefficient of multiple correlation; TBI, traumatic brain injury.

Comparison of Critical Event Joint Angles

Peak hip, knee, and ankle joint angles during critical events of the gait cycle are displayed in Table 4. The only between-group differences occurred during terminal stance, with participants with TBI displaying less ankle dorsiflexion than comparison participants.

Comparison of Linear Variability (SD of Critical Event Joint Angles)

Variability measures based on SD of critical joint angles yielded significant between-group differences at each joint (Table 5). Generally, SD of critical joint angles were higher for the TBI group (6 of 11 comparisons significant) across the hip, knee, and ankle.

Comparison of Nonlinear Variability (LyEs)

Three-dimensional state space plots for an exemplar participant with TBI and comparison participant are displayed for walking (Figure 2A) and elliptical training (Figure 2B). A comparison of maximum LyE indicated a tendency toward increased divergence (ie, reduced overlap of movement trajectories representing consecutive cycles) in the movement pattern for participants with TBI across all joints and conditions as compared to their comparison group counterparts (Figures 2A and B). However, no significant differences were documented between participants with TBI and comparison groups (Table 6).

Walking Versus Elliptical Training

Motion Profile Similarities

Visual inspection of hip and knee sagittal plane motion profiles revealed strong similarities between walking and elliptical training, as evidenced by CMC values greater than 0.87 for both participant groups. However, participants were generally positioned in greater flexion during elliptical training compared with walking. Ankle motion profiles displayed the least similarity between elliptical training and walking (Table 3 and Figures 1A, B, and C, respectively).

Comparison of Critical Event Joint Angles

Elliptical training resulted in significantly greater flexion across all joints compared with walking for 10 of 11 comparisons (Table 4). Only final knee position during loading response did not differ significantly.

Comparison of Linear Variability (SD of Critical Joint Angle)

Variability measures using SD of critical joint angles yielded significant differences between treadmill walking and elliptical training at each joint (Table 5). Generally, SDs of critical joint angles were higher for the elliptical trainer condition (5 of 11 comparisons significant) across the hip, knee, and ankle.

Comparison of Nonlinear Variability (LyEs)

During walking, maximum LyE values were significantly greater than those during elliptical training at the hip. In contrast, maximum LyE values at the ankle were significantly greater during elliptical training compared with walking (Table 6).

Interaction Between Groups and Conditions

There were no significant interactions between groups and conditions identified for peak critical event joint angles (Table 4), SD of critical joint angles (Table 5), or maximum LyEs (Table 6).

DISCUSSION

After severe brain injury, individuals often face lifelong challenges with walking and staying physically active. This

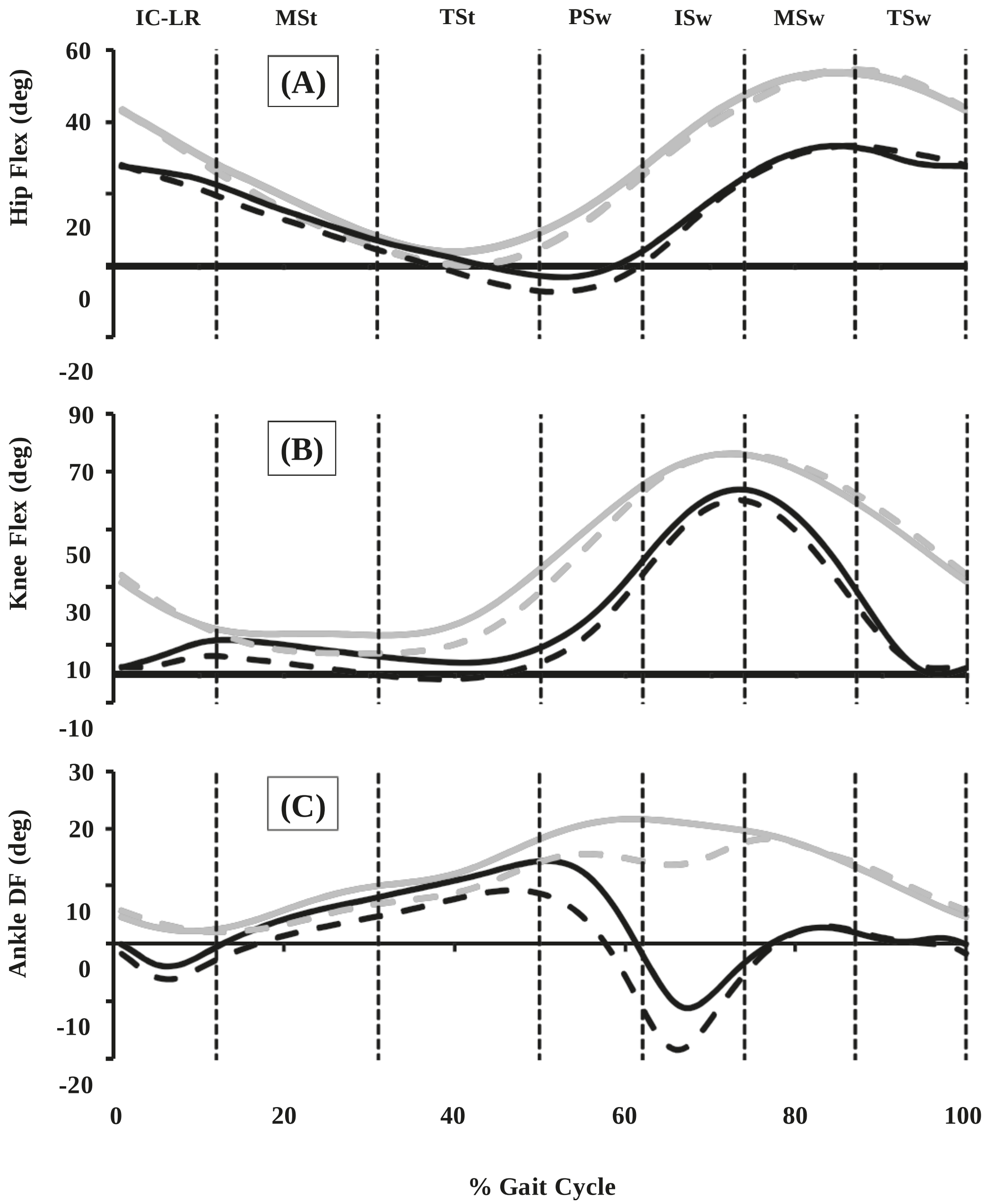


Figure 1. Hip (A), knee (B), and ankle (C) sagittal plane joint angles for comparison (solid) and brain injured participants (dashed) during treadmill walking (black) and elliptical training (gray). deg, degrees; DF, dorsiflexion; Flex, flexion; IC, initial contact; ISw, initial swing; LR, loading response; MSt, mid stance; MSw, mid swing; PSw, preswing; TSt, terminal stance; TSw, terminal swing. Negative values indicate hip extension, knee hyperextension, and ankle plantar flexion.

is concerning given the importance of exercise for improving the health and wellness of all individuals living in the United States. The study reported provides insights into the movement abilities of individuals with chronic severe TBI and the potential to use an elliptical device as a therapeutic tool for task-related gait training.

Brain injury frequently results in strength impairments and it is reasonable to expect that these changes alter movement patterns compared to those without a disability. While the participants with TBI in this study were on average 10 years postinjury, evidence from clinical measures (ie, muscle strength, spasticity, gait, balance scores) as well as the kinematic measures (ie, motion patterns, variability) during walking and elliptical training indicate that they continued to demonstrate residual deficits. Consistent with our first hypothesis, participants with TBI displayed less ankle dorsiflexion during terminal stance both while treadmill walking and while elliptical training compared to comparison participants. It is possible that the plantar flexor spasticity documented in 4 of the participants with TBI may have limited dorsiflexion. Although not measured, it is also possible that some participants with TBI had limited plantar flexor extensibility (ie, contractures) that limited dorsiflexion.

Beyond the differences in dorsiflexion motion, lower limb walking motion profiles were very similar between the 2 groups as evidenced by CMC values 0.85 or greater at

Table 4. Critical Joint Angles Recorded for Participants With TBI (n = 10) and Comparison Participants (n = 10) During Walking and Elliptical

		X (SD) Angles (°) for[a]						
		Participants With TBI		Comparison Participants				
Joint	Phase	Walking	Elliptical	Walking	Elliptical	Group	Condition	Group × Condition Interaction
Hip	IC	28 (10)	43 (8)	28 (7)	43 (4)	NS $P = 0.905$	EL > TW $P < 0.001$	NS $P = 0.800$
	TSt peak ext	−8 (5)	−1 (8)	−3 (6)	4 (4)	NS $P = 0.085$	TW > EL $P < 0.001$	NS $P = 0.937$
	MSw peak flex	35 (9)	55 (7)	34 (6)	54 (5)	NS $P = 0.784$	EL > TW $P < 0.001$	NS $P = 0.950$
Knee	IC	3 (8)	34 (9)	4 (6)	32 (5)	NS $P = 0.818$	EL > TW $P < 0.001$	NS $P = 0.258$
	LR final position	6 (15)	14 (10)	12 (9)	16 (5)	NS $P = 0.071$	NS $P = 0.147$	NS $P = 0.066$
	TSt peak ext	−3 (7)	7 (13)	4 (3)	13 (5)	NS $P = 0.061$	TW > EL $P < 0.001$	NS $P = 0.977$
	ISw peak flex	64 (9)	77 (5)	64 (4)	77 (4)	NS $P = 0.844$	EL > TW $P < 0.001$	NS $P = 0.686$
Ankle	IC	−2 (6)	6 (4)	0 (4)	5 (4)	NS $P = 0.909$	EL > TW $P < 0.001$	NS $P = 0.141$
	LR peak PF	−7 (5)	2 (4)	−4 (4)	2 (3)	NS $P = 0.390$	TW > EL $P < 0.001$	NS $P = 0.190$
	TSt peak DF	10 (5)	15 (6)	14 (3)	19 (6)	Control > TBI $P = 0.048$	EL > TW $P < 0.001$	NS $P = 0.688$
	MSw final position	−3 (6)	13 (5)	−1 (3)	13 (4)	NS $P = 0.756$	EL > TW $P < 0.001$	NS $P = 0.161$

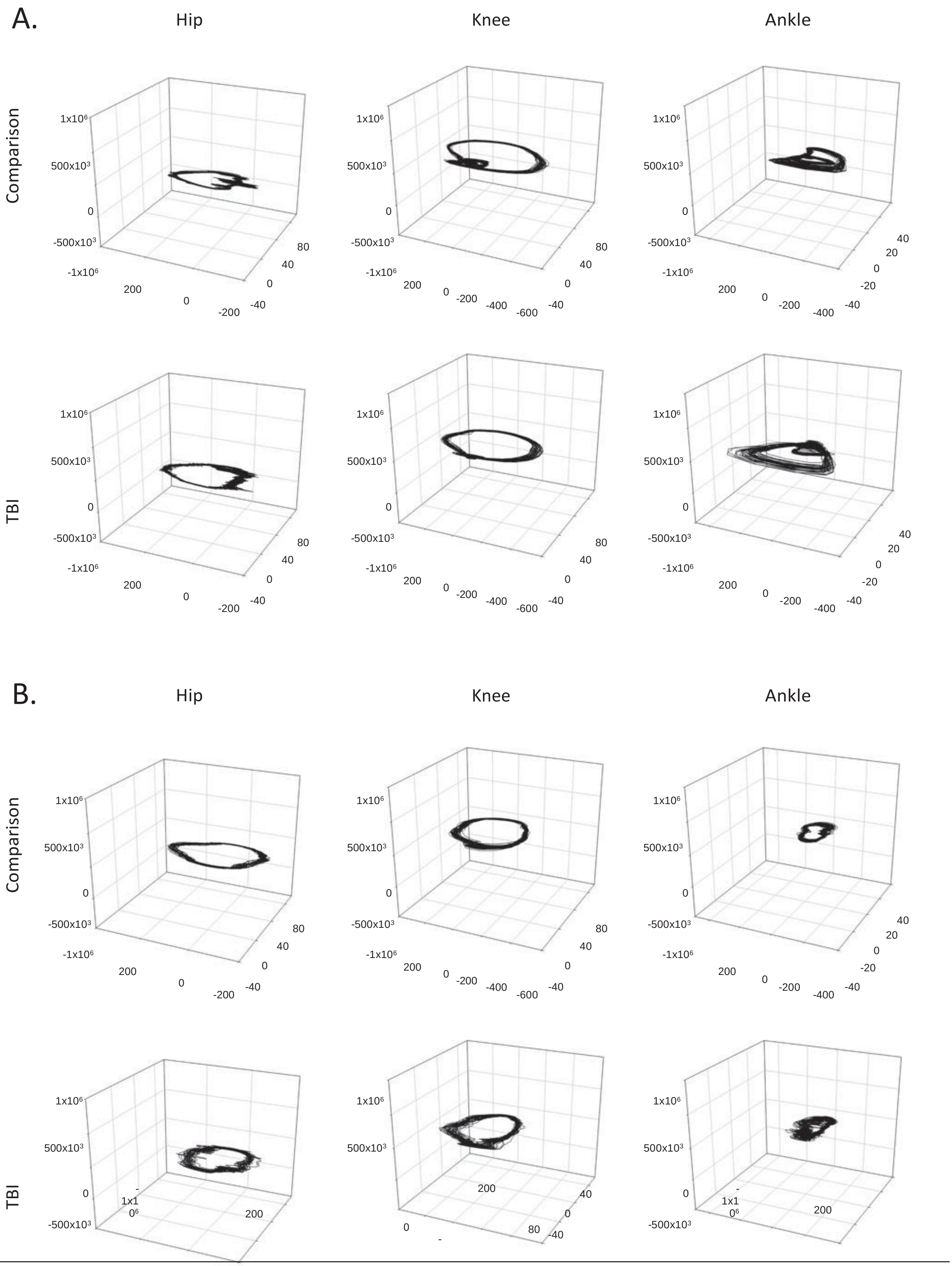
Abbreviations: EL, elliptical training; IC, initial contact; ISw, initial swing; LR, loading response, MSw, mid swing, NS, nonsignificant; TBI, traumatic brain injury; TSt, terminal stance; TW, treadmill walking.

[a]Positive values indicate flexion of the thigh and knee and dorsiflexion of the ankle. Negative values indicate extension of the thigh and knee and plantar flexion of ankle.

Table 5. Peak Critical Event Joint Angle Standard Deviations for Participants With TBI (n = 10) and Control Participants (n = 10) During Walking and Elliptical

		X (SD) of Peak Joint Angle Standard Deviation						
		Participants With TBI		Comparison Participants				
Joint	Phase	Walking	Elliptical	Walking	Elliptical	Group	Condition	Group × Condition Interaction
Hip	IC	2.0 (0.8)	2.1 (0.9)	1.2 (0.5)	1.3 (0.4)	TBI > Control $P = 0.002$	NS $P = 0.727$	NS $P = 0.914$
	TSt	1.6 (0.8)	1.8 (0.7)	0.8 (0.4)	1.3 (0.4)	TBI > Control $P = 0.001$	NS $P = 0.127$	NS $P = 0.623$
	MSw	2.0 (0.9)	1.9 (1.2)	1.8 (1.3)	1.2 (0.4)	NS $P = 0.213$	NS $P = 0.230$	NS $P = 0.390$
Knee	IC	1.7 (0.9)	3.0 (1.1)	1.3 (0.5)	2.2 (0.7)	TBI > Control $P = 0.029$	EL > TW $P < 0.001$	NS $P = 0.468$
	LR	1.7 (0.8)	3.5 (1.8)	1.4 (0.7)	2.2 (0.6)	TBI > Control $P = 0.022$	EL > TW $P = 0.004$	NS $P = 0.182$
	TSt	1.0 (0.6)	2.0 (0.8)	1.0 (0.4)	1.9 (0.6)	NS $P = 0.817$	EL > TW $P < 0.001$	NS $P = 0.619$
	ISw	1.6 (1.0)	1.7 (0.5)	0.9 (0.3)	1.5 (1.0)	NS $P = 0.106$	NS $P = 0.101$	NS $P = 0.388$
Ankle	IC	1.8 (1.0)	1.8 (0.8)	1.5 (1.3)	1.4 (0.4)	NS $P = 0.191$	NS $P = 0.865$	NS $P = 0.871$
	LR	1.1 (0.4)	2.0 (1.1)	0.8 (0.3)	1.2 (0.3)	TBI > Control $P = 0.019$	EL > TW $P = 0.004$	NS $P = 0.242$
	TSt	1.0 (0.4)	2.1 (1.0)	0.9 (0.4)	1.6 (0.9)	NS $P = 0.284$	EL > TW $P < 0.001$	NS $P = 0.368$
	MSw	2.1 (1.1)	1.7 (0.7)	1.0 (0.6)	1.4 (0.6)	TBI > Control $P = 0.011$	NS $P = 0.890$	NS $P = 0.184$

Abbreviations: EL, elliptical training; IC, initial contact; ISw, initial swing; LR, loading response; MSw, mid swing; NS, nonsignificant; TBI, traumatic brain injury; TSt, terminal stance; TW, treadmill walking.



A.
Hip
Knee
Ankle
Comparison
TBI
1x10⁶
500x10³
0
-500x10³
-1x10⁶
B.
Hip
Knee
Ankle
Comparison
TBI

0

0 -200 -400

80 -500x10³

40 -1x10⁶

0 200

-600 -40 0 -200 -400

4
0
2
0
0
-
2
0
-40

Figure 2. Three-dimensional plots of sagittal plane time series for 30 consecutive strides of treadmill walking (A) and elliptical training (B) for the hip, knee, and ankle of exemplar comparison and participants with TBI where joint position (Pos.) [X] is plotted versus angular velocity (Vel.) [X ($t-n$)] and angular acceleration (Accel.) [X ($t-2n$)]. Less overlap of the trajectories indicates greater divergence (ie, larger maximum LyE values).

Table 6. Comparison of Ankle, Knee, and Hip Maximum LyE Between Participants With TBI (n = 10) and Comparison Participants (n = 10) for Walking and Elliptical

	X (SD) Maximum LyE						
	Participants With TBI		Comparison Participants				
Joint	Walking	Elliptical	Walking	Elliptical	Group	Condition	Group × Condition Interaction
Hip	0.072 (0.028)	0.064 (0.032)	0.068 (0.029)	0.047 (0.014)	NS $P = 0.263$	TW > EL $P = 0.020$	NS $P = 0.456$
Knee	0.054 (0.013)	0.059 (0.009)	0.050 (0.012)	0.050 (0.010)	NS $P = 0.138$	NS $P = 0.452$	NS $P = 0.415$
Ankle	0.084 (0.013)	0.110 (0.030)	0.080 (0.018)	0.091 (0.030)	NS $P = 0.126$	EL > TW $P = 0.034$	NS $P = 0.366$

Abbreviations: EL, elliptical training; NS, nonsignificant; TW, treadmill walking.

the hip, knee, and ankle. Given findings of Ochi et al[31] of greater deficits in spatiotemporal gait characteristics during early phases of brain injury recovery, it is probable that the relatively high functional status of participants with TBI biased results toward greater similarity in movement profiles than may have occurred if individuals with lower FIM scores (ie, <5) had participated. Future studies that include individuals with more limited walking capacity and strength could reveal greater motion profile differences between groups.

Previously, variability measures in people recovering from TBI focused only on measuring the amount of variability present in selected stride characteristics. Given findings that independent ambulators demonstrate greater step pattern variability compared to comparison participants,[32] it is reasonable to expect that they would also demonstrate greater variabil- ity in lower extremity movement patterns. Consistent with our second hypothesis, participants with TBI did display an increased amount of variability compared to comparison participants. Higher critical event joint angle SDs indicated that participants with TBI had greater movement amplitude variability than comparison participants; those with TBI demonstrated tendencies toward increased variability with significantly higher SD of critical joint angles for 6 of 11 between group comparisons across the hip, knee, and ankle. Similarly, a tendency toward increased divergence in the movement trajectories (ie, higher LyEs) was observed for participants with TBI compared to comparison participants across all joints and conditions; however these differences did not achieve statistical significance. The greater variability in peak joint angles across strides and the slightly altered temporal variability may be explained partially by the need to rely on several different movement strategies to accommodate muscle weakness and balance deficits. The finding that neither the SD of critical joint angles nor the LyEs for either group equaled zero suggests that both the participants with TBI and comparison participants incorporated multiple movement strategies, while the finding that the LyEs did not approach 0.5 suggests that neither group became overly disorganized while using the multiple movement strategies to accomplish the tasks of treadmill walking and elliptical training.

Understanding similarities and differences between walking and elliptical training kinematic should provide clinicians, fitness trainers, and individuals recovering from a brain injury with valuable insights into the task-relatedness and nature of variability between the 2 activities. Consistent with the third hypotheses, hip and knee motion patterns demonstrated strong similarities between walking and elliptical training for both TBI and comparison participants as evidenced by high CMC values for both groups at the hip (>0.87) and knee (0.88). Similarities at the ankle, however, were not as pronounced, given the lower CMC values for the TBI and comparison groups (0.54 and 0.57, respectively). These findings suggest that even in the presence of weakness and balance deficits, elliptical training provides a foundation for kinematically similar locomotor retraining, particularly as regards movement of the hip and knee, a finding that expands upon previous research documenting task-relatedness of elliptical training to walking in individuals without known pathology.[10] However, it is not clear to what extent differences in sensory feedback between elliptical and treadmill training (eg, cutaneous plantar receptors, load receptors, hip flexor, and gastrocnemius length feedback) influence the degree to which elliptical training may be utilized as an equivalent locomotor task.

Despite high CMC values for hip and knee profiles between activities, several notable differences in critical event joint angles were documented. In particular, all 3 joints were generally postured in greater flexion during elliptical training compared with walking. These findings were consistent with those previously documented.[10] The observed differences between the movement profiles of the 2 activities can be explained in part by the impact of the pedal trajectory of the elliptical trainer on limb posture. Disparities in pedal height during elliptical training (ranging from 7 to 20 cm across stride lengths and cycle phases) resulted in an increased need for flexion at the hip, knee, and ankle (ie, dorsiflexion) compared to walking. Future research, aimed at better understanding the impact of different pedal trajectories on lower extremity kinematics, should help guide selection of devices that offer the greatest task specificity to walking.

Because of the fixed motion pattern and sustained double-limb support imposed by the foot pedals of the elliptical device, we believed that the degrees of freedom available during elliptical training would be constrained. Therefore, our final hypothesis had been that variability would be less during elliptical training compared with walking. Only the finding of lower hip LyE values during elliptical training suggested that the hip movement patterns were more constrained during elliptical training compared with walking. In contrast, higher ankle LyE values during elliptical training compared with walking provided evidence for greater divergence in the cyclical trajectories of the ankle (ie, less consistency in overlap from cycle to cycle). The significantly higher SD of critical joint angles of the knee and ankle that were identified for 5 of 8 critical event joint angles during elliptical training compared with walking also emphasized the greater variability in distal kinematic patterns across movement cycles during elliptical training. The ability to have sustained contact of all 4 limbs with the elliptical trainer throughout each movement cycle may have allowed sufficient flexibility for the knee and ankle to explore different strategies for completing each elliptical path. This would indicate that even though the elliptical machine dictates the path of the pedal trajec- tory, the joints are able to move freely in the sagittal plane (ie, they are not fixed to a specific trajectory). Future research that compares variability during elliptical training while using all 4 extremities to the use of only the legs may help elu- cidate the impact of additional support points on variability measures.

Clinicians can select from an array of elliptical trainer settings to encourage variability and development of the highly pliable movements necessary for walking in complex environments. For instance, the wide range of available stride lengths available on some elliptical trainers can provide an opportunity for simulating challenges commonly encountered when ambulating in the community. Elliptical trainers that have both moveable and static handles allow users to vary hand positions and strategies for maintaining elliptical motion while providing differing levels of challenge for balance and stability. Similarly, the ability to train at different speeds and use varying resistance levels and pre-programmed training modes allows modifications to be made for task complexity and demands. Finally, the recent development of an accessible motorized elliptical trainer[10,33,34] may provide people in the early phases of recovering from a brain injury with a tool that enables more independent practice of an activity that closely mimics walking and challenges key muscles, yet allows for mass repetition and variability critical for skill development.

LIMITATIONS

Participants with TBI were matched with comparison participants; however, there was a high degree of inconsistency in the functional impairments in the TBI group. Even though all participants with TBI had initially sustained a severe TBI, considerable differences existed in the long-term effects on gait as evidenced by 4 of 10 participants scoring perfect on the Dynamic Gait Index. In addition, there was no control for length of time since injury. Average time since injury was 10 years. Future work controlling for severity or residual impairments appears warranted. Because of lack of information regarding variability and elliptical training for people with TBI, sample size was underestimated; however, this study provides valuable information to guide statistical power assumptions for future research. For instance, the results of this study indicate that an additional 9 participants would be needed in each group to detect significant differences in several of the LyE comparisons. Only sagittal plane motions and variability were explored in this study. It is possible that variability occurring in the other planes (ie, frontal and transverse) may be altered. Further work exploring motions outside of the sagittal plane would enhance the understanding of the amount and structure of variability for participants with TBI and during elliptical training.

CONCLUSIONS

The lifelong challenges that individuals with severe brain injury face indicate the importance of identifying training devices to improve walking and fitness that are accessible in a community-based setting. In persons with TBI, training on the elliptical device was associated with movement patterns that were similar to the patterns during walking; however elliptical training was associated with greater variability of peak joint angles. The findings from this study suggest that elliptical trainers could be used to help individuals practice complex movements similar to walking.

REFERENCES

1. Thurman DJ, Alverson C, Dunn KA, Guerrero J, Sniezek JE. Traumatic brain injury in the United States: a public health perspective. *J Head Trauma Rehabil*. 1999;14(6):602-615.
2. Basford JR, Chou LS, Kaufman KR, et al. An assessment of gait and balance deficits after traumatic brain injury. *Arch Phys Med Rehabil*. 2003;84(3):343-349.
3. Perry J. The use of gait analysis for surgical recommendations in traumatic brain injury. *J Head Trauma Rehabil*. 1999;14(2):116-135.
4. Cantin J-F, McFadyen BJ, Doyon J, Swaine B, Dumas D, Vallace M. Can measures of cognitive function predict locomotor behavior in complex environments following brain injury. *Brain Inj*. 2007;21(3):327-334.
5. Summers MJ. Increased inattentional blindness in severe traumatic brain injury: evidence for reduced distractibility. *Brain Inj*. 2006;20(1):51-60.
6. Katz DI, White DK, Alexander MP, Klein RB. Recovery of ambulation after traumatic brain injury. *Arch Phys Med Rehabil*. 2004;85:865-869.
7. Talmage EW, Collins GA. Physical abilities after head injury. *Phys Ther.* 1983;63(12):2010-2017.
8. Hillier SL, Sharpe MH, Metzer J. Outcomes 5 years post-traumatic brain injury (with further reference to neurophysical impairment and disability). *Brain Inj*. 1997;11(9):661-675.
9. O'Sullivan SB, Schmitz TJ. *Physical Rehabilitation*. 5th ed. Philadelphia, PA: FA Davis Company; 2006.
10. Burnfield JM, Shu Y, Buster TW, Taylor AP. Similarity of joint kinematics and muscle demands between elliptical training and walking: implications for practice. *Phys Ther*. 2010;90(2):289-305.
11. Huisinga JM, Schmid KK, Filipi ML, Stergiou N. Persons with multiple sclerosis show altered joint kinetics during walking after participating in elliptical exercise. *J Appl Biomech*. 2012;28(3):249-257.
12. Jackson K, Merriman H, Campbell J. Use of an elliptical machine for improving functional walking capacity in individuals with chronic stroke: a case series. *J Neurol Phys Ther.* 2010;34:168-174.
13. Husinga JM, Fillipi ML, Stergiou N. Elliptical exercise improves fatigue ratings and quality of life in patients with multiple sclerosis. *J Rehabil Res Dev.* 2011;48(7):881-890.
14. Stergiou N, Harbourne R, Cavanaugh J. Optimal movement variability: a new theoretical perspective for neurologic physical therapy. *J Neurol Phys Ther*. 2006;30(3):120-129.
15. Harbourne R, Stergiou N. Movement variability and the use of nonlinear tools: principles to guide physical therapist practice. *Phys Ther.* 2009;89:267-282.
16. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Hum Mov Sci*. 2011;30(5):869-888.
17. Greenwald BD, Burnett DM, Miller MA. Congenital and acquired brain injury. 1. Brain injury: epidemiology and pathophysiology. *Arch Phys Med Rehabil*. 2003;84(S1):S3-S7.

18. Kidd D, Stewart G, Baldry J, et al. The functional independence measure: a comparative validity and reliability study. *Disabil Rehabil*. 1995;17(1):10-14.
19. Whitney S, Wrisley D, Furman J. Concurrent validity of the Berg Balance Scale and the Dynamic Gait Index in people with vestibular dysfunction. *Physiother Res Int*. 2003;8(4):178-186
20. Pardasaney PK, Latham NK, Jette AM, et al. Sensitivity to change and responsiveness of four balance measures for community-dwelling older adults. *Phys Ther*. 2012;92(3):388-397.
21. Hislop HJ, Montgomery J. *Daniels and Worthingham's Muscle Testing: Techniques of Manual Examination*. 8th ed. Philadelphia, PA: WB Saunders Company; 2007.
22. Cooper A, Musa IM, Van Deursen R, Wiles CM. Electromyography characterization of stretch responses in hemiparetic stroke patients and their relationship with the Modified Ashworth Scale. *Clin Rehabil*. 2005;19:760-766.
23. Buzzi UH, Stergiou N, Kurz MJ, Hageman PA, Heidel J. Nonlinear dynamics indicates aging affects variability during gait. *Clin Biomech*. 2003;18:435-443.
24. Dingwell JB, Cusumano JP, Cavanagh PR, Sternad D. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *J Biomech Eng*. 2001;123(1):27-32.
25. Perry J, Burnfield JM. *Gait Analysis: Normal and Pathological Function*. 2nd ed. Thorofare, NJ: Slack Inc; 2010.
26. Wolf A, Swift JB, Swinney HL, Vastano JA. Determining Lyapunov exponents from a time series. *Physica*. 1985;16D:285-317.
27. Myers SA, Johanning JM, Stergiou N, Celis RI, Robinson L, Pipinos II. Gait variability is altered in patients with peripheral arterial disease. *J Vasc Surg*. 2009;49:924-931.
28. Stergiou N. *Innovative Analyses of Human Movement: Analytical Tools for Human Movement Research*. Champaign, IL: Human Kinetics; 2004.
29. Cignetti F, Decker LM, Stergiou N. Sensitivity of the Wolf's and Rosenstein's algorithms to evaluate local dynamic stability from small gait data sets. *Ann Biomed Eng*. 2012;40(5):1122-1130.
30. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res*. 1989;7(6):849-860.
31. Ochi F, Esquenazi A, Hirai B, Talaty M. Temporal-spatial feature of gait after traumatic brain injury. *J Head Trauma Rehabil*. 1999;14(2):105-115.
32. Niechwiej-Szwedo E, Inness EL, Howe JA, Jaglal S, Mcllroy WE, Verrier MC. Changes in gait variability during different challenges to mobility in patients with traumatic brain injury. *Gait Posture*. 2007;25(1):70-77.
33. Nelson CA, Burnfield JM, Shu Y, Buster TW, Taylor A, Graham A. Modified elliptical machine motor-drive design for assistive gait rehabilitation. *Trans ASME J Med Devices* 2011;5:021001.1-7.
34. Burnfield JM, Shu Y, Buster TW, Taylor A, Nelson CA. Impact of elliptical trainer ergonomic modifications on perceptions of safety, comfort, workout and usability by individuals with physical disabilities and chronic conditions. *Phys Ther*. 2011;91(11):1604-1617.

Did you know...?

Efficacy versus *Effectiveness*: Research studies are conducted under controlled conditions with participants who meet specific inclusion and exclusion criteria. When between-groups differences are identified in these studies, the reader may conclude that the *efficacy* of the intervention has been demonstrated. However, demonstrating the *effectiveness* of that intervention requires that its value be demonstrated under typical clinical practice conditions. Under these conditions participants may have disorders with different degrees of acuity, severity, co-morbidity, and there may be differences in adherence, environment, and other factors that have potential to influence the outcome.