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Comparison of elliptical training, stationary cycling, treadmill walking and overground walking

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Keywords

gait; rehabilitation; locomotor; variability; coordination

INTRODUCTION

Promoting, maintaining and enhancing gait function are common therapeutic goals in neurorehabilitation, with the recent proliferation of devices to assist patients and clinicians towards achievement of those goals. While these devices may facilitate practice of the locomotor pattern, their superiority in enhancing gait outcomes remains uncertain [1]. Comparative evaluation of the biomechanical and coordinative aspects of various device-driven locomotor training tasks may provide some insights into their potential effectiveness in improving overground ambulation. Multiple studies have compared treadmill to overground gait kinematics, some including kinetic and electromyographic (EMG) data as well. Some small kinematic differences have been identified across these modalities, but are generally considered inconsequential [2, 3]. Riley and colleagues [4] demonstrated the “essential equivalence” of treadmill and overground walking, showing differences in 12/22 kinematic parameters in 33 healthy adults, with all but one less than 2° in magnitude. Lee and Hidler [5] confirmed the similarity in kinematic patterns, but noted more pronounced EMG differences responsible for preserving the nearly identical motions. Some studies have reported contradictory directions of differences, for example, increased [6] or decreased [4] peak hip flexion on the treadmill. Some differences may be attributed to the novelty of the treadmill for some subjects which often dissipate with a short practice (less than 10 minutes) [7]. Some clinical populations, e.g. the elderly [8], may have more difficulty accommodating to the treadmill and require additional practice.

Far less research has evaluated the biomechanical similarity of other lower extremity device-augmented training tasks to walking. Elliptical training was recently compared to overground walking in 15 healthy young males with a primary focus on joint loading; however, three-dimensional kinematic differences were also reported [9]. Excursions were similar at the knee and hip, but the curves were shifted into greater flexion at each joint particularly for the second half of the cycle with the elliptical. Kinematic differences from

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overground walking were also identified in the frontal and transverse planes. These findings were largely replicated by Burnfield and colleagues [10] who additionally demonstrated that not all elliptical trainers are 'equal' with some more closely resembling walking kinematics and kinetics.

In addition to the degree of biomechanical similarity other considerations for choice of a device include relative differences in joint stress which are important if repeated use of a training device is indicated. Degree of similarity in the coordinative aspects of the movements in the device including the degree of interlimb reciprocity versus synchrony and of intralimb coupling versus isolated control may also affect the degree of transfer. For example, walking involves reciprocal movements of the legs and arms, in contrast to a task such as rowing which involves bilaterally synchronous motions. Persons with disorders such as stroke or cerebral palsy often demonstrate more synergistic or constrained movement patterns within a limb such as massed flexion or extension during gait. These impair selective motor control or the ability of joints to move independently of each other [11, 12, 13]. The extent to which selective control may be required or reinforced may differ across tasks, especially for tasks like cycling and elliptical stepping which constrain motion to a pre-set arc, is also as yet unknown. The degree of ankle and knee intralimb coupling during gait in 78 children from ages 3-13 years without disability was -0.70 [14]. This indicated that these joints tended to move in opposition; whereas in 34 children with CP of similar ages, the correlation was $+0.70$ indicating a high and significantly greater ($p < 0.05$) degree of synergism. Additionally, to enhance training and neuroplastic effects, there should be an underlying rhythm or pattern but it should optimally be variable and flexible rather than rigid [15].

Our goals were to compare lower extremity kinematics of cycling, elliptical training, overground and treadmill walking in healthy adults, and to provide greater justification for further exploration of the use of these tasks and other exercise tasks or robotic devices in gait rehabilitation. We hypothesized that elliptical kinematics would more closely resemble walking than does cycling and therefore may have greater transfer to overground gait patterns. We further hypothesized that both elliptical training and cycling would show a similar or greater degree of interlimb coordination than treadmill or overground walking due to the interlimb coupling inherent in those devices.

METHODS

Participants

Ten healthy young adults (6 males) participated. Mean age was 22.7 ± 2.9 years (range 20-29 years), mean height was 173.5 ± 9.8 cm (range 155-191 cm), and mean mass was 69.5 ± 9.8 kg (range 49.5-79.1 kg). The protocol was approved by our Human Subjects Institutional Review Board and written informed consent was obtained from all individuals.

Procedures

Three-dimensional lower extremity kinematics were collected with a ten-camera motion capture system (Vicon, Lake Forest, CA), at a sampling rate of 120 Hz. For the static trial, 23 markers were used, then knee and ankle markers were removed. Participants first performed overground walking (W) at a self-selected speed so that temporal-spatial data could be obtained to individually determine speed and cadence for the other conditions, as well as for kinematic data collection of overground walking. Each participant was instructed to walk at a "normal, comfortable pace" across the laboratory, approximately 8 meters. Two motion detection sensors determined mean walking speed in real-time from the first four

trials in one direction. Cadence was manually calculated by visualizing the gait events in Nexus in order to count steps per unit time and averaged across trials.

Subjects then performed treadmill walking (T), cycling (C), and elliptical (E) trials in random order. The average W speed and cadence were used to pace the other device conditions. Treadmill speed was matched to W velocity. During C and E, participants were instructed to match W cadence with the aid of a metronome.

A split-belt Bertec TM-06-B treadmill (Columbus, OH), Monark 818E stationary cycle (Vansbro, Sweden), and Nordic Track CX1000 elliptical trainer (Logan, UT) were used for the respective test conditions. The elliptical was set at the maximum radius allowable in the device to encourage as much excursion as possible. The cycle seat height was adjusted for each subject's leg length to allow for nearly full extension at the maximal point in the revolution. Participants wore their own exercise shoes for all tasks. Each was given several minutes as needed to familiarize themselves with each device and pace and were instructed to indicate to us when they felt they were comfortable with each. Data were then captured while the subject performed the task as instructed for approximately 1-2 minutes per condition.

Data analysis

Five right and left cycles were extracted for analysis from each condition using the time-synchronized marker data (initial foot contact for consecutive footfalls for walking trials, and the most anterior point of consecutive revolutions for elliptical and cycling trials). Variables extracted per cycle and averaged across five cycles were mean and peak excursion at the pelvis, hip, knee, and ankle.

Time-series data for five cycles were time normalized to 51 data points (at 2% increments) and averaged.. The Gait Deviation Index (GDI) was used to compute a single score for each subject on each modality by inputting the averaged time series of pelvic and hip angles in all three planes, knee flex/extension, ankle dorsi/plantarflexion, and foot progression [16]. Data from each subject's W condition was used to create a reference GDI value of 100 with values closer to 100 representing a greater similarity to W.

To examine the degree of similarity between movement patterns of different joints pairs on the ipsilateral extremity (intra limb coordination) or the same joint across extremities (interlimb coordination), Pearson correlation procedures were performed with values closer to +1.0 indicating that the paired joints were moving in concert and values closer to -1.0 indicating that they were moving in opposition using time-series data across two full right and left gait cycles for each subject from one representative trial. The coefficient of variation for cadence (CV) was computed across trials and averaged per condition.

Mixed model ANOVA procedures with post hoc tests where indicated were used to compare all subject values across conditions ($P < 0.05$).

RESULTS

Cadence was higher during T than W ($p < 0.001$) and E ($p < 0.024$) (Table 1). Sagittal plane kinematic plots are shown in Figure 1. These indicated that T excursion, position, and variability were very similar to those of W as reported previously. The only difference was greater hip rotation excursion during W. When comparing all four conditions, knee excursion was the only parameter that showed no differences. E and C showed unique patterns of differences from W. E showed higher values on all but two parameters compared to both W and T, indicating either greater magnitude in terms of excursion, or greater

flexion or anterior tilt, internal rotation, or adduction depending on the joint and plane of motion of interest. Two exceptions were ankle motion, which showed no differences and mean hip rotation, which was more external on the elliptical. C demonstrated greater minimum and maximum flexion at the knee than W and T, more posterior pelvic tilt, more external hip rotation, less ankle plantar flexion and less overall ankle excursion. Compared to C, E showed greater anterior pelvic tilt minimum, maximum and excursion, greater hip and ankle excursion and greater peak ankle dorsiflexion. While C had similar knee excursion as E, the curve was shifted towards more flexion throughout the cycle. The hip was also more flexed and had less excursion during C.

GDI Principal Components Analysis by Modality

Mean GDI values showed no difference between T (94.6) and W (100.0±10SD); whereas the E GDI (29.4) and the C GDI (−9.7) were different from each other and from T and W ($p<0.001$). The radar plot (Figure 2) depicts the 10 individual GDI scores and relative distances across conditions.

Intralimb and Interlimb Coordination

During both W and T, there is not tight intralimb coupling between the hip and knee although the correlation value is positive (range of 0.10-0.22 for W and 0.16-0.22 for T). The hip and ankle and knee and ankle tended to act in opposition. This is dramatically different during C where all three joints are highly coupled and constrained to move in unison. E shows greater hip and knee coupling than W and T but ankle coupling with the hip or knee during E is minimal to negative.

Figure 3 shows the intralimb coupling comparisons across tasks for the right side. Small but significant right to left differences were found for most correlations, but in no case did the direction differ. For hip and knee coupling, all comparisons between the walking conditions and E and C were different ($p<0.05$) with the only exception being with the right-side comparison of W and T. For the ankle - hip coupling, W did not differ from T. Most notably, C differed from all other conditions on both sides. E differed from W and T only on the right. For the ankle and knee, all comparisons were different except for between W and T, with results identical across sides ($p<0.05$).

Figure 4 shows the interlimb coupling comparisons across tasks. Across limbs, the hips moved with a high degree of reciprocation regardless of condition with the only difference being C which showed greater reciprocation than during W ($p<0.05$). At the knee, the degree of reciprocation did not differ between W and T, but was greater during both C and E, with C showing the higher amount. At the ankle, W and T did not differ, nor did C or E, but all comparisons of C or E with W or T were significant.

Trial-to-trial temporal-spatial variability of cadence was low (less than 8.0% for all conditions) but was greater during C and E (7.3% and 5.8%, respectively) than during W and T (3.0% and 2.7%, respectively).

DISCUSSION

The primary goal here was to explore potential locomotor training alternatives to the treadmill by evaluating their kinematic similarity. As has been shown previously, nearly complete kinematic similarity between treadmill and overground walking was demonstrated here by evaluation of individual joint positions and excursions and, for the first time, by a composite value based on principal components analysis, the GDI. In contrast, the patterns for the two other locomotor tasks studied here were markedly divergent from the two walking tasks and from each other. The GDI for cycling was the furthest from overground

walking and elliptical stepping was closer, but still tended to be closer to cycling than to walking overground or on the treadmill. Kinematic similarity of different locomotor tasks, specifically treadmill and elliptical stepping compared to overground, has been shown to be subserved by a greater dissimilarity in muscle timing, amplitude and joint forces across the same tasks [5, 9]. Whether or how similarities or differences in specific aspects (e.g., kinematics versus EMG or loading patterns) differentially affect the degree of skill transfer is not yet known.

A recent review on the effectiveness of treadmill training for improving gait in pediatric rehabilitation suggested that transfer of skills from treadmill to overground walking was probable, but hardly definitive [17]. Supported treadmill training has failed to show superiority over overground training, even though some argue that this enables even more normal kinematics for some patient groups (e.g. less knee crouch) and better arm coordination [18] than overground practice. While these factors may enhance transfer, weight support systems restrict practice of trunk control and can also diminish loading thereby potentially decreasing the level of afferent input and limiting strength gains. Loading is also substantially decreased through the lower extremities during cycling because of the seated support; whereas with the elliptical, the only upright support provided is through vertical handles that move in opposition to the legs. Resistance to motion can also be increased on both the elliptical and the cycle during training which could increase lower extremity strength and/or endurance capabilities and thereby improve gait performance. If walking is impaired because of lower extremity weakness, elliptical training with or without added resistance beyond full body weight is may surpass the treadmill in improving gait outcomes.

Kinematic results also showed that both the elliptical and cycle involve greater knee excursion than walking and for the cycle, this is the only joint where motion increases. As explained recently by Burnfield, the circular arc of motion inherent in the elliptical vertically elevates the non-loaded leg far more than would occur during walking where the limb barely needs to clear the supporting surface. This forces greater excursion in multiple planes primarily at more proximal joints such as the hips and pelvis as compared to the other three conditions. The elliptical flexes the hip as it moves backwards differing from the linear motion of the treadmill that brings the hip back into extension. It has been questioned whether the hip merely needs to go towards the direction of extension or achieve motion beyond neutral to enhance stepping coordination [9] and requires further study.

The potential for an intervention to improve coordination is of great interest to the neurorehabilitation community. It is possible that too much intralimb constraint, as seen with cycling and to a lesser degree, the elliptical, may impair development of selective control. If greater selective ankle control were desired, the elliptical may be helpful. If poor reciprocal interlimb coordination is impairing the ability to step, cycling may be most effective in training this, assuming that the individual is actively engaged in the task.

The cycle and elliptical had a more variable pattern than walking which was expected since the subjects had to impose their own rhythm on these devices and many lacked experience on these which typically increases variability. It is also possible that subjects may not have been given sufficient time to practice during testing in order to reduce their variability in those tasks. Treadmill belts, motor-assisted cycles, and some robotic gait devices, e.g. Lokomat, may be utilized in a manner that enforces a rhythm that is too regular causing the spinal cord to habituate [14]. However, for those who cannot produce an underlying reciprocating rhythm, external assistance may be required for them to practice this effectively.

Kinematic similarity does not imply similarity of motor control and lack of kinematic similarity does not mean that tasks are totally unrelated. For example, even though cycling was shown to be dissimilar to walking using the GDI, there is evidence of shared neural circuitry in cycling and walking and both require reciprocal motor coordination. Beyond kinematics, differences in sensory inputs and body orientation also exist and may affect transfer across tasks. These and other factors that may influence transfer such as similarity in strength and endurance requirements, among others, must also be considered. Furthermore, we cannot assume that motor learning, and hence task transfer, is similar in normal and pathological motor systems. It is also possible that the kinematics reported here for any given task such as treadmill walking may vary slightly if other devices are used for that task than those used here.

The elliptical not only has greater kinematic similarity to walking than cycling, as demonstrated here, but also vertically loads the extremities and requires arm coordination suggesting it may have some distinct advantages not only over cycling, but perhaps treadmill training with a harness. Since patients are holding on, this may enable less stable individuals to exercise safely but in a more challenging manner than with a harness and free arms. The hypothesis that elliptical training will produce a greater treatment effect for improving gait function than stationary cycling in more functional patients with CP and other neurological disorders is plausible and should be tested. For more involved patients, greater weight support and motorized, therapist-mediated or FES-assisted control may be necessary at least initially to help generate an underlying rhythm and enable effective practice of coordinated motor patterns.

CONCLUSION

As exercise and robotic devices are increasing employed for gait training in patient populations, their individual and relative effectiveness compared to conventional gait training must be evaluated. Our data reinforce the kinematic and coordinative similarity of treadmill and overground walking. Cycling showed the largest GDI difference from overground, with elliptical closer but still a significant distance from all three. If kinematic similarity was the sole determinant of skill transfer, then a treadmill would be the universally preferred device. However, other devices may promote different aspects of the target task that may be even more important for transfer, particularly in varied rehabilitation applications. Cycling showed greater hip reciprocation. Further evaluation of these devices in neurological gait disorders is needed.

Acknowledgments

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Figure 1. Sagittal plane kinematics showing peak position in both directions, total excursion and standard deviation across the four conditions: overground Walking (W), Treadmill walking (T), Elliptical (E) & Cycling (C).

Figure 2.

The radar plot of individual GDI scores for all ten participants for each condition showing Cycling (C) as the innermost circle, then Elliptical (E) with Treadmill (T) mostly inside and nearly overlapping overground Walking which is the solid line (W). Each 10-point difference is equivalent to one standard deviation.

Figure 3. Intralimb coordination in each of the four conditions with a higher value indicating that the joints are moving in concert and a lower value indicating moving in opposition with significant differences ($p < 0.05$) from overground walking indicated.

Figure 4. Interlimb coordination showing the degree of reciprocity (negative values) versus synchrony (positive values) across contralateral joints with significant differences ($p < 0.05$) from overground walking indicated.

Table 1

Mean cadence (steps/min) and standard deviation (SD) for overground Walking (W), Treadmill walking (T), Elliptical (E) and Cycle (C).

Condition	Mean	SD
W	107.9	8.3
T	115.8	11.0
E	108.4	12.4
C	109.9	15.1