Effects of Slope on Backward Locomotion

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Abstract

The purpose of this study was to investigate the effects of an inclined and declined slope on kinematic properties and muscle activation magnitudes during backward walking (BW). Eleven participants (24.6 ± 4.1 yrs, 68.5 ± 14.6 kg, 1.7 ± 0.1 m) performed a three day protocol at their preferred walking speed before data collection. These adaptation sessions were conducted at a level slope (control), a 10% grade incline (+10%) and a 10% decline (-10%). Dependent variables included sagittal plane joint range of motion (ROM) of the hip, knee, and ankle joints, stride time (ST), stride frequency (SF), and integrated EMG of four lower extremity muscles. One-way repeated measure ANOVAs with pairwise comparisons were conducted for each dependent variable (α = 0.05). In both experimental conditions, significant differences were found in ST ($p < 0.001$) and ROM of the hip, knee, and ankle joints ($p < 0.01$). Compared to level walking, SF was not significantly different at a decline ($p = 0.391$) but was increased at an incline ($p = 0.003$). Integrated EMG exhibited significant increases in four major muscle groups (rectus femoris, tibialis anterior, gastrocnemius, and bicep femoris) at +10%. At a -10%, all muscles exhibited significant differences ($p < 0.001$), except the biceps femoris ($p = 0.052$). The results of this study suggest that increased muscle activity and knee ROM in inclined BW (+10%) may be beneficial in addressing physical conditions of the knee and extensibility of the hamstrings muscles. The added eccentric activity in declined BW may also lead to increased hamstring flexibility and provide a benefit in rehabilitation.

Keywords: Gait; EMG; Rehabilitation; Retro Walking; Treadmill

Abbreviations

3-D: Three-Dimensional; A/D: Analog to Digital; ANOVAs: Analyses of Variance; BW: Backward Walking; BF: Biceps Femoris; DBW: Declined Backward Walking; EMG: Electromyography; FW: Forward Walking; GA: Gastrocnemius; IBW: Inclined Backward Walking; iEMG: Integrated Electromyography; RF: Rectus Femoris; ROM: Range of Motion; SF: Stride Frequency; ST: Stride Time; TA: Tibialis Anterior

Introduction

Backward walking (BW) is one therapeutic modality that has recently shown potential to be useful for addressing various conditions. It has been utilized to improve hamstring flexibility and various physical conditions of the knee, including osteoarthritis [1-4]. Yet the biomechanics of BW has not been well-described to validate its use as a therapeutic modality.

In comparing forward walking to BW, many similarities are noted in their kinetic and kinematic properties as well as their muscle activation patterns. There is evidence to suggest that BW is similar to forward walking, except that their kinematic characteristics are reversed with respect to the direction of the motion [5-11]. The angular velocities of the hip, knee, and ankle joints have been found to be

similar and the muscles that are activated are simply reversed in direction [6,8]. The muscles that typically contract concentrically during forward walking are found to be eccentric in BW, and vice versa [6,8,10,11].

Some of the differences between forward walking and BW can be explained by the asymmetrical nature of all the joints involved, with the ankle being most pronounced [6,9,11]. Because of the structural arrangement of the ankle joint relative to the foot, the synonymous gait pattern to the heel contact and toe off in FW would be seen in BW as the toe contact and heel off. Because of this change in position of the ankle joint when the heel leaves the ground during BW, the ankle is forced to increase its range of motion in order to properly clear the ground as the body propelled backward [6,10]. The hip and the knee exhibit decreased range of motion because they have lesser contribution in assisting foot clearance in comparison to FW [10].

Using this evidence as a basis, practitioners have adopted BW as a potential modality to intercede in a variety of diagnoses, including nonspecific chronic lower back pain, or for other rehabilitative patients, such as those recovering from strokes. Dufek., *et al*. [12] described that BW can be an effective modality to alleviate chronic lower back pain by increasing hamstring flexibility, which has been shown to be a major contributor to the pain experienced by patients [2,13,14]. Yang., *et al*. [15] provided evidence to show that stroke patients could improve several gait markers, including stride length, velocity, and symmetrical gait patterns by supplementing their therapy with BW.

BW as a therapeutic intervention has been shown to have potential in reducing clinical symptoms and improve overall functionality. Additional research has modified this intervention by including backward running since evidence has shown that it can increase quadriceps muscle strength while putting less strain on the patellofemoral joint [16]. Backward walking on an incline has also been adopted because the added perturbation could enhance some of the beneficial muscle strengthening properties that level BW provided [5,17]. While these studies show the effectiveness of BW as a potential therapeutic exercise modality, additional research could better explain which components of BW could specifically contribute to different diagnoses and symptoms. The purpose of this study was to investigate the effects of an inclined and declined slope on kinematic properties and muscle activation magnitudes during BW.

Materials and Methods

Participants

Eleven participants (24.6 ± 4.1 yrs, 68.5 ± 14.6 kg, 1.7 ± 0.1m, 5 males, 6 females) between the ages of 18 and 35 years were recruited for this study. Exclusion criteria consisted of any pain in the ankle, knee, or hip joints, or a previous history of surgery in any of these joints. All participants were briefed on the study, and then signed an informed consent as approved by the Protection of Human Subjects Committee at the affiliated institution. Participants were informed to wear tight fitting dark shorts and shirts, or were provided with such clothing for the duration of the laboratory measurement phase of the study to ensure the visibility of the markers used for measurement. Participants were also encouraged to wear comfortable walking shoes and were asked to wear the same shoes for all trials.

Protocol

Because BW on a treadmill was a novel task for some study volunteers, all participants underwent three practice sessions to adapt to the skill as well as to choose a preferred walking speed. Before data collection, all participants underwent two days of practice sessions. A third session was incorporated just before data collection to ensure accommodation. Participants began with a BW trial on a level, 0% slope for up to two minutes. During this interval, participants were allowed to adjust their walking speed to a preferred velocity. Once confirmed, the participants maintained that velocity and performed a practice trial for five minutes. Then, participants performed two more 5-minute practice trials under each condition; one with an inclined, +10% slope, and one with a declined, -10% slope, at the same velocity specified during the first practice trial. These three practice trials were conducted for each session for two consecutive days prior to the day of data collection.

During data collection, participants walked on a motor-driven treadmill (AM6500-TM) with a Vicon 3-D motion video camera system (Version 2.1.1; 120 Hz), consisting of 12 infrared Bonita cameras tracking their movement. Participants were first instrumented with surface electrodes to measure muscle activation (EMG) using a Delsys wireless EMG system (2000 Hz; 16-bit, 64 channel A/D board). The electrodes (36 x 28 mm) were digitally monitored and data were acquired using a Trigno Personal Monitor EMG System (Model DS-T02; 2000 Hz). The Delsys EMG System was linked with Vicon Nexus Software (Version 2.1.1; 120 Hz), to simultaneously capture both EMG and motion capture data in accordance to time. Reflective hemispheric markers (16 mm diameter spheres) were attached to participants following the guidelines of the Lower Body Plug-In Gait Model utilized by the Vicon Nexus Software (Version 2.1.1).

On the day of data collection, electrodes and reflective markers were placed on the participants. Prior to electrode placement, the skin was shaved at the area of placement, then cleaned and abraded at the muscle belly following procedures as specified by Konrad (2005). Electrodes were attached to the rectus femoris, biceps femoris, tibialis anterior, and medial gastrocnemius with double sided tape, aligning the direction of the muscle fibers, as detailed on the instructions manual of the Delsys EMG System. Sixteen reflective markers were attached with double-sided tape guided by the Lower Body Plug-In Gait Model in Vicon Nexus (Version 2.1.1).

After completion of marker and electrode placement, participants was ready for data collection. The walking speed was averaged from the recorded walking speeds from the previous two days of practice. This speed was used for all three conditions on the third day. For each independent variable condition, participants were instructed to walk and were allowed three minutes of practice to ensure adaptation. Following this practice trial, data were captured for a thirty second period. Participants were not notified of when this capture took place to prevent them from changing their gait. This procedure was conducted at the level slope, and the experimental conditions that followed were counterbalanced with a downhill (-10%) slope, and uphill (+10%) slope.

Statistical Analysis

Data from the thirty second data collection from each condition were processed using Vicon Nexus software to calculate joint angles from the position markers in the sagittal plane. The kinematic data were then processed using MatLab and filtered with a low-pass Butterworth filter with a frequency cutoff at 4 Hz. From the position and joint angular data extracted from the Vicon system, kinematic parameters were calculated. These included joint range of motion, stride time, and stride frequency.

The EMG data were also processed through MatLab and filtered with a low-pass Butterworth filter at a frequency cutoff of 25 Hz. These data were further processed using a full-wave rectified method by taking the absolute value of each data point.

An integrated EMG (iEMG) value was calculated by summing the overall activation level across time. For variables with respect to a time cycle, an entire gait cycle was calculated using change in direction of velocity of kinematic markers.

One-way repeated measures ANOVAs were conducted for each dependent kinematic variable across the three slope conditions to examine any significant differences among the conditions for each variable. Pairwise comparisons were examined following significant F-statistics (α = .05). Muscle activity was analyzed using iEMG, which was accomplished by calculating the overall summation of muscle activity over the 30 second period. Analysis of iEMG allows for interpretation of overall muscle activity within each time cycle. The end summation of the iEMG was then analyzed using a one-way repeated measures ANOVA to determine any significant differences in the overall muscle activation across the three slope conditions and followed up with pairwise comparisons for significant differences.

Results and Discussion

Kinematics

The mean and standard deviation values for joint range of motion can be found in table 1 to represent the data in each of the three conditions. In all three joints, there were significant differences when comparing the range of motion between a level condition and ei-

ther an inclined or declined condition. In the hip joint, the range of motion on an incline was significantly less (p < 0.001), while a decline exhibited a significant increase (p < 0.001). The knee joint showed a significant increase in range of motion (p < 0.001) and a significant decrease at a decline (p < 0.001). In the ankle joint, both an incline (p < 0.001) and decline (p = 0.006) exhibited an increase in range of motion.

	Incline	Level	Decline
Hip (deg)	21.6 ± 5.8*	29.6 ± 7.5	39.5 ± 8.8*
Knee (deg)	40.8 ± 8.6*	38.1 ± 9.4	36.5 ± 10.0*
Ankle (deg)	33.6 ± 7.2*	26.7 ± 5.6	27.4 ± 6.2*
Stride Time (seconds)	.945 ± .16*	1.00 ± .17	1.03 ± .17*
Stride Frequency (steps/30 sec)	49.7 ± 3.2*	46.7 ± 2.5	45.5 ± 2.4

***Table 1:** Average and standard deviation values of range of motion and stride characteristics across conditions.*

* denotes significant difference from level condition at p <.05

The mean and standard deviation values for stride time and stride frequency can be found in table 1 to represent the data in each of the three conditions. Stride time significantly decreased at an incline (p < 0.001) and significantly increased at a decline (p < 0.001). Stride frequency was measured for each leg in each participant, and the average between the two legs used to determine the overall stride frequency in each condition. A significant increase was found in stride frequency at an incline (p = 0.003), with no significant difference in stride frequency observed at a decline (p = 0.391).

EMG

The mean and standard deviation values for the iEMG values can be found in table 2. In the rectus femoris, there were significant differences at an incline (p = 0.024) and at a decline (p < 0.001). A significant difference was seen between the level and incline conditions in the biceps femoris (p < 0.001), but not in comparison to the decline condition (p = .052). Significant differences were exhibited in the tibialis anterior at both the incline (p = 0.011) and the decline (p < 0.006), as well as in the gastrocnemius at both conditions (both at p < 0.001).

	Incline	Level	Decline
Rectus Femoris	175 ± 114*	153 ± 43	173 ± 57*
Biceps Femoris	171 ± 45*	190 ± 78	196 ± 84
Tibialis Anterior	94 ± 180*	62 ± 82	114 ± 260*
Gastrocnemius Medialis	143 ± 218*	89 ± 125	175 ± 294*

***Table 2:** Average and standard deviation values of integrated electromyographic (microvolts).*

* denotes significant difference from level condition at p <.05

One purpose of this study was to investigate changes in muscle activation magnitudes when changing the inclination of the treadmill surface. Backward walking at a treadmill inclination of +10% has been shown to be the minimum angle in comparison to level grade at which significant differences have been observed in kinematic properties and muscle activation patterns [17]. In the current study, there were several observed differences with Inclined Backward Walking (IBW) and Declined Backward Walking (DBW) that may provide variation to further improve the current practice of backward walking as an intervention for various physical conditions of the knee.

IBW may serve as an alternative exercise to BW on a level slope due to the increased involvement for the knee joint, as well as the increased iEMG exhibited in the current study in major muscle groups in the lower extremity. The overall iEMG values for the rectus femoris, gastrocnemius, and tibialis anterior in IBW were significantly greater, except in the biceps femoris, which was significantly decreased. This result is supported by Myatt., *et al.* [18], who found similar muscle activation patterns due to the increased metabolic needs imposed by the nature of the direction of motion during BW. Due to the joint asymmetry involved when walking backward, much of the force production is contributed by the concentric contractions of the quadriceps muscles, leaving the hamstring muscles to exhibit lower muscle activation overall because it is consistently in a negative eccentric contraction [18]. Similarly to IBW, the overall muscle activation during DBW was increased in the rectus femoris, tibialis anterior, gastrocnemius, but not the biceps femoris muscle. The results of the current study show that there is more muscle activity in the quadriceps in IBW, which may suggest that the hamstring has overall less strain and is exhibiting more eccentric activity, but further analysis of the EMG activity is required.

In the analysis of kinetic parameters, stride time, stride frequency, and joint range of motion were compared in all three slope conditions. In IBW, stride time significantly decreased, while increasing in DBW. Hunter., *et al.* [19] found that downhill forward walking was correlated with changes in stride time and muscle activity, particularly in the added eccentric activity that was exhibited to help sustain the body's moving center of mass during locomotion. A similar pattern was seen in BW in the current study but with the opposite muscle, following the evidence that's has shown that BW is mostly a reversal of muscle activation patterns in BW, particularly in the quadriceps and hamstring muscles [6,7,18]. Due to the nature of the direction of motion, BW exhibits higher concentric contractions in the quadriceps muscle to propel the body forward, leaving the hamstring muscles to eccentrically contract to help slow down and control knee extension [18]. This supports the increased stride time results in DBW in the current study that may attributed to more eccentric contractile activity in the hamstring muscles. The results of this study show that IBW exhibits an increase in overall range of motion in the knee while DBW exhibits a significant decrease.

BW has been shown to be useful as treatment modalities for conditions such as hamstring overuse related injuries [1,2] and in knee rehabilitation [4,16,20,21]. The purpose of the current study was to investigate muscle activation magnitudes and kinematic properties of BW when the slope condition was inclined and declined. It was hypothesized that there may be properties of BW on a changing slope that may enhance the effects caused by the increased eccentric contractile activity that has been shown to be beneficial properties of BW [18]. The results of this study show support for both IBW and DBW as potential variations of exercise to the recently popular addition of BW on a level slope.

For rehabilitation of the knee that are constrained due to injury or surgery, such as post-operative anterior cruciate ligament patients, one of the biggest constraints in therapy treatments is the inability to bear weight due to the compressive patellofemoral forces [16,21]. Kinetic analyses have shown that BW and backward running as an effective treatment option before patients return to forward walking and running because it has lesser compressive forces in the knee while also building muscle strength in the quadriceps [16,21]. The current study has found that overall muscle usage is increased in both slope conditions. Future research should aim to focus on the kinetic properties of BW on an incline and decline slope in addition to any muscle strength building components. The findings may benefit clinician when determining proper training intensity during sloped BW.

The current study also found that there was lower hamstring muscle activity, potentially due to increased eccentric contractile activity [7,18], as well as increased range of motion in IBW. This may be beneficial for those with hamstring overuse related injuries because eccentric training regimens targeting the hamstring muscle have been found to increase hamstring flexibility [7,18,22-24]. Previous studies have shown that such regimens that incorporate dynamic range of motion training can effectively increase hamstring flexibility similarly to static stretching [22,25-33]. Further research is recommended to examine whether IBW conditions might increase eccentric muscle contractions as well as benefitting athletes or patients to increase hamstring flexibility and lowering any pain.

Conclusion

In summary, hip, knee and ankle lower extremity joints exhibited significant differences in range of motion in both experimental conditions (+10% and -10%). Stride time exhibited a significant increase at -10% and a significant decrease at +10%. Stride frequency increased significantly at +10%. No differences were observed for the decline condition. The iEMG significantly increased in the biceps femoris, rectus femoris, tibialis anterior, and gastrocnemius muscles at +10%, while only the rectus femoris, tibialis anterior, and gastrocnemius exhibited significant increases at -10% in comparison to the level condition. Additional research is suggested to continue to explore the potential rehabilitation and/or therapeutic effects of IBW and DBW.

Conflict of Interest

None of the contributing authors declare any conflict of interest with this research project.

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