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Comparison of kinetic strategies for avoidance of an obstacle with either the paretic or non-paretic as leading limb in persons post stroke

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ABSTRACT

The task of stepping over obstacles is known to be particularly risky for persons post stroke. A kinetic analysis informing on the movement strategies used to ensure clearance of the leading limb over an obstacle is, however, lacking. We examined obstacle avoidance strategies in six community dwelling stroke survivors comparing the use of paretic and non-paretic limb as the leading limb for clearance over obstacles measuring 7.5% and 15% of their total leg length. Subjects were able to increase foot clearance height in both limbs in order to avoid the two obstacles. Obstacle clearance with the non-paretic limb leading was associated with positive knee flexor work that increased when stepping over each obstacle, thus showing a normal knee strategy that flexes both the knee and the hip for foot clearance. There was also slightly increased hip flexor contribution for non-paretic obstacle clearance that was the same for both obstacle heights. When the paretic limb led during obstacle clearance, there was also evidence of an increased knee flexor moment, suggesting a residual knee strategy, but it was less pronounced than for the non-paretic limb and was assisted by greater vertical hip elevation and additional positive hip flexor work that both gained greater importance with increased obstacle height. These findings suggest that rehabilitation should explore the ability to improve the residual, but less powerful, knee flexor strategy in the paretic limb in specific patients, with further promotion of a hip flexor and limb elevation strategy depending on patient deficits and obstacle height.

1. Introduction

A stroke can lead to various motor impairments, many of which affect locomotor function. The motor impairments following a stroke include muscle weakness, spasticity, and impaired coordination, which lead to gait disturbances [1,2]. Furthermore, there is an increased risk of falls in this population [3] often resulting from changing the course of locomotion [4] or from overcoming obstacles in the path of locomotion [5–7]. The ability to successfully step over obstacles in stroke survivors increases when such training is included in a rehabilitation program [8,9]. Recent work, however, has shown that improvement only occurs when the non-paretic limb is leading [10]. To fully understand how persons post stroke are able to successfully clear obstacles, one must understand the movement strategies used in both the paretic and non-paretic leading limbs.

To date, most of the research that has examined obstacle clearance in people with a previous stroke has focused on kinematic characteristics. Said et al. [11] have shown that lower limb joint flexion does not significantly differ between paretic and non-paretic limbs during obstacle clearance. However, MacLellan et al. [12] showed greater knee flexion in the non-paretic limb during obstacle clearance. In the frontal plane, participants post stroke have greater hip abduction during obstacle clearance, suggesting the use of circumduction to assist in clearance [13]. To fully understand how persons post stroke execute this task, however, a kinetic analysis is required.

Winter and Eng [14] argued that a kinetic analysis provides insight into the central nervous system's goals when producing a movement. When healthy adults step over obstacles, a 'knee strategy' is used whereby mechanical energy is generated about the knee joint to flex both the knee and hip simultaneously due to passive interaction forces [15,16]. However, this is not always the

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case with musculoskeletal changes or constraints. For example, people with a below-knee prosthetic device have been shown to generate mechanical energy at the hip joint (a 'hip strategy') to elevate the lower limb when stepping over an obstacle [17]. Following a knee joint replacement, individuals tend to increase work in the hip flexors as well as to use a vertical hip elevation strategy to step over an obstacle [18]. Nothing is known, however, about strategies used when the body is intact, but when motor control is compromised by a stroke.

The purpose of the current study was to determine what movement strategies participants who have had a stroke use to clear an obstacle in the course of locomotion, when instructed to lead with the paretic or non-paretic limb. It was hypothesized that leading with the non-paretic limb would reveal a knee flexion strategy similar to that demonstrated in healthy persons, while leading with the paretic limb would involve a modified strategy due to motor control deficits. Exploring these strategies may provide information that can be used to guide rehabilitation interventions aimed at increasing mobility and decreasing falls following a stroke.

2. Methods

Six adults with a previous stroke (three women, age: 56.2 ± 5.4 years, height: 1.66 ± 0.05 m, mass: 63.1 ± 9.0 kg, time since stroke: 22.5 ± 23.8 months, walking speed 0.96 ± 0.24 m/s) participated in the study. Of these participants, four had sustained a stroke on their right side and lesion locations included the Sylvain Fissure (four participants), basal ganglia (1), and the internal capsule (1). One participant wore an ankle-foot orthosis (AFO) throughout the experiment. The same participants have been reported in a separate study [12]. All participants provided informed consent prior to participation in the study according to ethics guidelines from the Quebec Rehabilitation Institute and Laval University.

In the experimental protocol, participants stepped over two different obstacles on separate trials with respective heights normalized to 7.5 and 15% of the participant's leg length (greater trochanter to floor) (corresponding to average heights of 0.07 and 0.14 m, respectively). The obstacle was custom-made using a wooden base outfitted with a spring loaded maroon-colored (for contrast) vinyl window blind. Four vertical rods connected by long strips of metal allowed for the adjustment of obstacle height. The width and depth of the obstacle was 0.129 and 0.05 m respectively in all conditions. The trial started approximately 3–4 steps from the obstacle, with participants alternating between the paretic and the non-paretic side as lead foot on separate trials as they stepped over the obstacle with both limbs. Participants were generally successful with the task and contact with the obstacle rarely occurred. Control trials with no obstacle were used to examine level walking. A minimum of two trials per condition were collected.

Full body three-dimensional kinematic data were collected at 60 Hz by means of a 3-bar Optotrak system (Northern Digital Inc., Waterloo, Canada). Non-collinear triads of infrared markers were attached to the feet, shanks, thighs, pelvis, trunk, and head. A calibration trial was collected and anatomical landmarks (heel, toe, 5th metatarsal, medial/lateral malleoli, medial/lateral femoral condyles, left/right iliac crests, and left/right anterior superior iliac spines) were digitized to determine their virtual trajectories offline. Kinematic data were filtered offline using a dual-pass 2nd order Butterworth filter with a cut-off frequency of 6 Hz.

Ground reaction forces and moments were collected at 1000 Hz from each of the paretic and non-paretic stance limbs using an AMTI force platform (Advanced Mechanical Technology, Inc., Watertown, Massachusetts). Kinetic data were filtered offline using a dual-pass 2nd order Butterworth filter with a cut-off frequency of 50 Hz.

From these data, a 9-segment biomechanical model was used to examine leading limb movement strategies during obstacle clearance. The kinematic variables investigated in the current study were center of mass velocity in the anteroposterior (AP) direction, clearance height, hip elevation, and frontal plane lower limb movement. The center of mass AP displacement over the stride was determined using the stated biomechanical model and differentiated by time to determine the velocity and subsequently averaged over the stride. When stepping over the obstacle, clearance height was calculated as the vertical distance between the top of the obstacle and the toe at the instant of clearance. On average, this occurred at 37.4% and 38.4% of the swing phase in the paretic limb and at 32.3% and 33.0% in the non-paretic limb for the 7.5% and 15% obstacles, respectively. During level walking (when no obstacle was present), clearance height was calculated as the vertical distance between the toe and the ground at the point in the gait cycle corresponding to when the obstacle was cleared by the given limb during the obstacle trials. This represents the average point (as a percent of swing) across all obstacle clearance trials. Vertical hip elevation during the swing phase of gait was determined by subtracting the hip height at toe-off from the maximum hip height during swing. To examine lower limb movement in the frontal plane during obstacle clearance, the relative medio-lateral distance between the ankle and ipsilateral hip joint was calculated at each frame during the swing phase and this value at toe-off was subtracted from the maximal value during swing. This will be referred to as lower limb abduction where positive values indicate that the ankle was moved more laterally during swing with respect to the hip at toe-off and negative values indicate that the ankle was moved more medially.

Muscle moments about the ankle, knee, and hip were estimated using a custom-made computer program involving Newton–Euler inverse dynamics. Peak flexor muscle moments were then identified in the leading limb for each joint between toe-off and a point corresponding to the average % of swing that maximum toe height occurred across all obstacle conditions. Even though maximum toe height occurred in late swing for level walking, this was due to different dynamics related to foot repositioning and, therefore, the same period established for obstructed walking was used for level walking trials in order to compare early limb elevation dynamics across conditions. Muscle mechanical power was calculated by multiplying the muscle moment at each joint by the joint angular velocity during swing. By integrating the muscle mechanical power curve between toe-off and maximum toe height of the lead limb (as presented above), an estimate of the work done by the muscle to elevate the limb was determined. In addition, the work done by mechanical energy transfer to elevate the hip joint upwards was calculated by integrating the hip joint mechanical power curve (hip joint vertical reaction force multiplied by hip joint vertical velocity) between toe-off and maximum toe height.

Since one participant wore an AFO during the study, further examination of the data was warranted to ensure that this participant performed in a manner similar to the remaining participants. Since the measurements obtained for this participant were consistently within two standard deviations of the mean for all variables, they were therefore retained for the subsequent analyses. For each variable, a Friedman test was used to determine main effects for walking conditions (level walking, 7.5% obstacle, 15% obstacle) for each limb independently. If this test was found to be significant, a Wilcoxon test was then used to determine differences between walking conditions. Significant differences between limbs (paretic, non-paretic) were determined using a Wilcoxon test for each walking condition. Statistical significance was determined at $p < 0.05$.