“Changes in Lower Extremity Biomechanics as a Result of Feedback in Virtual Obstacle Crossing”

Spring 2018 Honors Thesis

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Introduction

Falls are one of the most common ways to sustain an injury. Many people each year are diagnosed with clinical conditions that cause gait dysfunction such as aging, stroke, neurological issues, or injury. These populations generally have greater difficulty navigating obstacles in their environment, and therefore, have an increased fall risk (Patla, Rietdyk, Martin, & Prentice, 1996). Fall risk is a substantial problem, but potentially could largely be preventable with proper training. In order to create a successful training program, it is important to identify risk factors that lead to falls. In older adult populations, falling occurs as a result from tripping over obstacles (Chou & Draganich, 1998). Successful obstacle crossing is crucial to safe ambulation. Obstacles may be static, such as a curb or stair, or dynamic, such as an animal or ball rolling into the gait trajectory path. Successful avoidance of these everyday occurrences reduces the risk of falling due to obstacle contact. If it is possible to train people to develop safer obstacle crossing strategies, then it can be possible to therefore reduce the risk of falls and consequent injury.

Previous studies have examined some of the biomechanical changes due to obstacle crossing and how obstacle contact may occur. Patla et al. (1996) tested for differences between the lead and trail limbs as an individual crosses over an obstacle to see if gait patterns adjusted for one limb over the other. They found that the velocity for the leading leg when stepping over an obstacle decreased significantly in relation to their normal walking velocity without an obstacle, but the velocity for the trail leg increased while stepping over the obstacle. They found this reason to likely be because when stepping over an obstacle, the lead leg has a greater chance to hit the obstacle with the toe, heel, or any part of the foot, whereas the trail limb's only possible point to contact the obstacle is the toe (Patla et al., 1996). Another potential reason why subjects increased the velocity of their trail limb during crossing could be due to the stability of the crossing. When lifting the lead leg, the center of mass of the body moves away from the obstacle, whereas when the trail leg is crossing the obstacle, the center of mass is moving forward, toward the obstacle, which is a more stable movement (Patla et al., 1996). When the trail limb does contact the obstacle, the person is less at risk for a serious injury because it is the more stable movement; however, as a result, people tend to not focus on the trail limb as much, which is a likely reason as to why the trail limb contacts obstacles most often.

One of the conditions mentioned to cause gait dysfunction is a natural change in the human body due to time: aging. A study showed that 32% of a sample of older adults at least 75 years of age living in a community-living environment fell at least one time in a year, with 24% of those falls causing serious injuries (Tinetti & Speechley, 1989). Chen et al. (1991) conducted a study in which they compared younger and older adult walking patterns and obstacle negotiating strategies. They found older adults used a slower approach speed to the obstacle and a significantly lower crossing speed over the obstacles than the younger adult subjects. The older adults also had significantly smaller distance from the obstacle to the heel of the lead foot at heel strike, heel-to-heel crossing step length, and step width. Finally, there was no statistical significance in foot clearance, defined as the minimum vertical clearance between the top of the obstacle and the lowest point on the sole beneath each foot (Chen, Ashton-Miller, Alexander, & Schultz, 1991). The older adults also tended to use more conservative and safer crossing strategies because when the toe of their lead foot reached the obstacle, it was 10% further forward in its swing pattern than in the young adult's crossing. Since the risk of a more serious fall is greater the earlier the toe contact occurs in the swing phase, it can be determined this method is inherently safer (Chen et al., 1991).

The older adult population may be more at risk to falls not because of their strategy, but because of their decreased range of motion in their hip, knee, and ankle angles compared to the young adults. In Chen et al. (1991), subjects were asked to maximally flex/dorsiflex and maximally extend/plantar-flex their hip, knee, and ankle joints and the angle measurements were recorded. Older adults had an average of ten degrees range of motion less than the younger adult subjects, which could be a large factor in the differences between the young and older adult populations (Chen et al., 1991). Chou and Draganich (1998) found that decreasing the horizontal distance between the lead toe and obstacle resulted in less hip, knee, and ankle flexion when the trail foot would be over the obstacle. They also found that as the horizontal distance between the toe and obstacle decreased, the vertical toe to obstacle distance of the trailing foot also decreased significantly (Chou & Draganich, 1998). As a further result, the closer the toe was to the obstacle, the more often the trail foot contacted the obstacle. All in all, control of the hip and knee flexion may be the most critical factor in fall risk for the elderly population.

Virtual reality technology can be a valuable tool to help measure and train people to navigate obstacles using safer strategies. There has been conclusive evidence to support treadmill training can improve usual walking patterns, but there is little literature to support training for obstacle crossing navigation (Mehrholz et al., 2010). Virtual reality is said to be able to provide visual, auditory, and haptic information for the enhancement of motor learning. This enhancement occurs through problem solving and multiple repetitions of movement to improve performance of the task at hand (Mirelman et al., 2011). Some advantages of virtual reality are that it provides a repetitive practice, feedback about performance, and motivation to endure practice (Holden, 2005). Combining treadmill training with virtual reality technology has been shown to improve gait speed, stride length, and increase the horizontal distance from the foot to the obstacle while negotiating an obstacle. This shows the subject is planning better for the obstacle with a more efficient and safer strategy (Mirelman et al., 2011). The most impressive and arguably the most important aspect of this virtual reality training is that the cognitive advancements have transferred from the treadmill to "real-world" situations (Holden, 2005; Mirelman et al., 2011). It can be argued that practicing in the real world is better than practicing in a virtual environment since it is in fact the real thing; however, it can be argued the complete opposite is true because virtual reality provides the ability to customize the tasks to make them easier or less dangerous, more fun, and quicker to learn because of the pivotal feedback (Holden, 2005).

The two things most important for learning to occur is practice and feedback. Virtual reality is able to provide both of these aspects of learning. Feedback is the information about performance or errors presented to the learner of a task, and is split into two types: task-intrinsic and augmented feedback (Schmidt & Lee, 2014). Task-intrinsic feedback includes visual, auditory, tactile, and proprioceptive sensory systems, whereas augmented feedback is performance related information that effects the focus of attention (Magill, 2001). Augmented feedback is then divided into either knowledge of performance—internal information about movement characteristics such as joint angles in relation to the body, or knowledge of results feedback—external information about the outcome of performance such as pass or fail (Schmidt & Lee, 1999). Feedback can be given before, during, or after performing the task, and could be directed toward errors of performance or correct technique of performance. There is no inherently right or wrong way to give feedback; however, the advantage of error information is that it aids skill acquisition, and the advantage of correct reinforcement is that it motivates the subject. Using both types of augmented feedback allows for the subject to correctly perform the skill or task and motivate them to achieve the performance goal (Magill, 2001).

Previous work in the Virtual Environment for Assessment and Entertainment Lab at the University of North Carolina at Greensboro has combined gait and obstacle negotiating strategies, virtual reality technology, and feedback to address fall risk. Using virtual reality for technology as mentioned before provides a safe, cost-effective, and easily modifiable way to train obstacle negotiation. Previous studies within our lab confirmed that learning to cross virtual obstacles transfers to the “real world” obstacle crossing tasks and that participants adopt a safer obstacle crossing strategy in terms of an increased foot clearance over the obstacle (LoJacono et al., 2017). Additionally, these newly developed safer obstacle crossing strategies are retained 48 hours later (LoJacono & Rhea, 2017). However, it remains unknown how the safer obstacle crossing strategies are achieved in terms of the joint angles at the hip, knee, and ankle due to virtual reality obstacle crossing training. Additionally, it is unknown if the feedback given within the virtual reality obstacle training affects these joint angle changes.

The purpose of this study was to use virtual reality obstacle crossing technology to detect changes in lower extremity joint angles as a result of different feedback situations. Variables of interest that I measured were the changes in hip, knee, and ankle angles from pre-to post-training as the subjects crossed over the real environment obstacle to see if there were any changes in strategies as a result of feedback or no feedback. I hypothesized that the no feedback group would not change their hip, knee, or ankle angles; since they would not know if they have passed or failed crossing the obstacle, they would not know to change their approach and joint angles to cross differently. I also hypothesized that I would see an increase in hip and knee angle flexion (knee raised higher and earlier) in the lead limb. The reason for this hypothesis is because the subjects would adapt this safer crossing strategy as a result from the feedback while crossing over the virtual obstacles.

Methods

Participants

Seventeen young healthy adults (21.8 ± 2.7 years; 1.69m ± 0.08m; 76.8kg ± 21.5kg) voluntarily participated in this study. Retroreflective markers were placed on specific anatomical landmarks for movement tracking within the motion capture Qualysis system. Participants crossed 10 real environment obstacles (pre-training test) to obtain a baseline of their normal obstacle crossing strategies. They then rested for 5 minutes before participating in the virtual reality obstacle crossing training. Participants were harnessed and placed on a treadmill at their normal, comfortable, self-selected walking speed with a projection screen containing the virtual environment 7 feet in front of the treadmill. The virtual environment contained a pathway with a 10cm tall virtual obstacle covering the horizontal distance of pathway and a virtual representation of the participants' feet. The virtual feet contained 4 markers, representing the toe, heel, and medial and lateral portion of the metatarsals. Participants were asked to cross the virtual obstacle with the virtual feet, which were controlled via their own anatomical feet. Participants crossed 15 virtual obstacles, rested for 5 minutes, and then crossed another 10 virtual obstacles. They then rested for an additional 5 minutes. To conclude the study, participants crossed 10 more real environment obstacles (post-training test).

Participants were be divided into two groups: No-Feedback and Combined-Feedback. The Combined-Feedback group (n=9) received visually given feedback within the virtual environment in two ways. Participants saw all foot markers turn green if they successfully cleared the obstacle, or red if one or more markers did not clear the obstacle. Secondly, there was a performance counter on the screen showing the total number of passes/fails. The No-Feedback group (n=8) did not receive any feedback, meaning they did not know whether or not they cleared the virtual obstacle successfully.

Data Reduction

The data from the Qualysis System was exported to Visual3D (C-Moition, Bethesda, MD). Lower-body models were built for each subject using the conventional gait model with a Coda pelvis. Flexion angles for the ankle, knee, and hip were then determined for each subject during pre- and post-training. The maximum flexion angle point and the mean flexion angle during crossing of the real-world obstacle of the lead foot were obtained for input into our statistical analyses.

Statistical Analyses

Individual 2 (group) by 2 (time) repeated-measures ANOVAs were conducted for each of the following variables of the lead foot: maximum ankle angle, mean ankle angle, maximum knee flexion angle, mean knee flexion angle, maximum hip flexion angle, and mean hip flexion angle. Follow-up pairwise comparisons were conducted for any significant main effects. Alpha level was set a priori to 0.05.

Results

Ankle Joint Angles

To examine changes at the ankle due to VR obstacle crossing training, a 2 (group) by 2 (time) repeated-measures ANOVA was conducted for each the maximum and the mean ankle angle. For the maximum ankle angle, there was no main effect of group ($F_{1,15} = 0.004$, $p = 0.95$), no main effect of time ($F_{1,15} = 1.12$, $p = 0.31$), and no interaction effect ($F_{1,15} = 0.00$, $p = 0.99$). For the mean ankle angle, there was no main effect of group ($F_{1,15} = 0.334$, $p = 0.57$), no effect of time ($F_{1,15} = 0.578$, $p = 0.459$), and no interaction effect ($F_{1,15} = 0.817$, $p = 0.38$).

Knee Joint Angles

To examine changes at the knee due to VR obstacle crossing training, a 2 (group) by 2 (time) repeated-measures ANOVA was conducted for each the maximum knee flexion angle and the mean knee flexion angle. For maximum knee flexion angle, there was no main effect of group ($F_{1,15} = 2.54$, $p = 0.13$), no effect of time ($F_{1,15} = 0.319$, $p = 0.58$), and no interaction effect ($F_{1,15} = 1.021$, $p = 0.328$). For mean knee flexion angle, there was no main effect of group ($F_{1,15} = 0.236$, $p = 0.634$), no effect of time ($F_{1,15} = 3.872$, $p = 0.068$), and no interaction effect ($F_{1,15} = 3.113$, $p = 0.098$).

Hip Joint Angles

To examine changes at the hip due to VR obstacle crossing training, a 2 (group) by 2 (time) repeated-measures ANOVA was conducted for each the maximum hip flexion angle and the mean hip flexion angle. For maximum hip flexion angle, there was no main effect of group ($F_{1,15} = 1.24$, $p = 0.28$) and no main effect of time ($F_{1,15} = 0.374$, $p = 0.55$). However, there was an interaction effect ($F_{1,15} = 4.69$, $p = 0.047$). The No Feedback group decreased maximum hip flexion angle from pre-training (69.40° ± 6.09) to post-training (67.56° ± 8.10), whereas the Combined Feedback group increased maximum hip flexion angle from pre-training (62.26° ± 9.82) to post-training (65.54° ± 10.20). For the mean hip flexion angle, there was no main effect of group ($F_{1,15} = 0.013$, $p = 0.91$), but there was an effect of time ($F_{1,15} = 7.76$, $p = 0.14$). Follow-up pairwise comparisons indicated that mean hip flexion significantly decreased from pre-training (16.26° ± 6.71) to post-training (14.97° ± 6.09; $p = 0.014$). There was also an interaction effect ($F_{1,15} = 12.87$, $p = 0.003$). The No Feedback group decreased mean hip flexion angle from pre-training (17.40° ± 6.11) to post-training (14.21° ± 5.35), whereas the Combined Feedback group increased mean hip flexion angle from pre-training (15.24° ± 7.42) to post-training (15.64° ± 6.92).

Table 1. Overall minimum and mean flexion angles for the ankle, knee, and hip. Negative numbers for the ankle indicate plantarflexion and positive numbers for the ankle indicate dorsiflexion. * = Significant effect of time ($p<0.05$).

	Joint	Pre-Training	Post-Training
Maximum Flexion Angle (degrees)	*Ankle*	32.57 ± 107.21	12.33 ± 105.56
	Knee	105.8 ± 18.48	107.52 ± 18.48
	Hip	65.62 ± 8.83	66.50 ± 9.05
Mean Flexion Angle (degrees)	*Ankle*	-53.56 ± 73.21	-52.89 ± 71.29
	Knee	21.53 ± 10.25	20.28 ± 9.31
	Hip *	16.26 ± 6.71	14.97 ± 6.09

Table 2. Minimum and mean flexion angles for the ankle, knee, and hip separated by group. Negative numbers for the ankle indicate plantarflexion and positive numbers for the ankle indicate dorsiflexion. NF = No Feedback group, CF = Combined Feedback group, ǂ = Significant interaction effect ($p<0.05$).

	Joint	Group	Pre-Training	Post-Training
Maximum Flexion Angle (degrees)	*Ankle*	NF	34.32 ± 117.90	13.84 ± 108.78
		CF	31.01 ± 104.01	11.00 ± 109.26
	Knee	NF	114.17 ± 14.17	112.95 ± 9.34
		CF	98.38 ± 105.81	102.69 ± 23.47
	Hip ǂ	NF	69.40 ± 6.09	67.56 ± 8.10
		CF	62.26 ± 9.82	65.54 ± 10.20
Mean Flexion Angle (degrees)	*Ankle*	NF	-42.14 ± 89.54	-42.26 ± 85.79
		CF	-63.70 ± 58.80	-62.34 ± 59.27
	Knee	NF	23.40 ± 8.99	20.89 ± 8.43
		CF	19.87 ± 11.52	19.73 ± 10.51
	Hip ǂ	NF	17.40 ± 6.11	14.21 ± 5.35
		CF	15.24 ± 7.42	15.64 ± 6.92

Discussion

The results showed that there was no significant ankle angle changes from pre- to post-training regardless whether the participant received feedback or did not receive feedback. There was no main effect of the group, no main effect of time, nor any interaction effect in maximum or mean ankle angle data collected. The ankle angle data showed large standard deviations for both maximum and mean flexion angle showing there may be a difference in strategical approach among all participants unrelated to their feedback group. It seemed some participants chose plantarflexion at the ankle over dorsiflexion, some chose the opposite, and some chose a more neutral route with minimum flexion. Each individual seemed to have their own strategy for crossing the obstacle, and the feedback did not seem to have any effect on their ankle strategy. A potential explanation is simply because of their natural walking patterns. Some people naturally step with large plantarflexion at the ankle whereas others step with large dorsiflexion. The goal for the participants was to clear the obstacle, so it did not matter if their toe was pointed high so that their heel would be the point of contact with the obstacle, or if the toe was pointed towards the floor in plantarflexion during the crossing. It was found that neither strategy had a significant effect from pre- to post-training in either of the feedback groups.

There was no significant knee angle data from pre- to post-training regardless whether or not the participant received feedback. Unlike the ankle, there was a trending towards significance with the mean flexion angle, especially in regard to the main effect of time. I had hypothesized that I would see an increase knee angle flexion (knee raised higher and earlier) in the lead limb, however the data seems to be trending in the opposite direction. With a larger participant population, we may be able to understand this effect more.

The main finding lies with the hip flexion angles. There was a time effect where participants increased from pre- to post-training when groups were collapsed. These results indicate that feedback is not necessarily needed to modify mechanics at the hip, rather that the virtual reality obstacle crossing environment causes a change in hip strategy. However, there was an interaction effect between groups for both the maximum and mean flexion angles. The no feedback group decreased in both categories from pre- to post-training, whereas the combined feedback increased from pre- to post-training for both, suggesting that the time effect is potentially driven by the combined feedback group.

However, feedback did play a role in the type of hip strategy executed. The no feedback group exhibited more extension in the lead limb from pre- to post-training; therefore, a lack of feedback leads to more hip extension. The combined feedback group exhibits more flexion in the lead limb as a result of the feedback. I hypothesized that I would see an increase in hip angle flexion in the lead limb, which was shown to be correct in the combined feedback group. A potential reason for this change in biomechanics is because the subjects adopted this safer crossing strategy as a result from the feedback while crossing over the virtual obstacles. If they failed to clear the obstacle, it is likely the first mechanical change an individual makes is to lift the lead leg higher, as shown in these results.

There were some limitations to this study which could potentially be the reason for finding insignificant results for the ankle and knee angles. First, there were a limited number of participants. With a larger population size, some trends, such as the ones found in the knee, may change from trends to significance. Secondly, some participants had to be excluded from the data due to an inability to model the joints properly, leading to a smaller sample size than proposed. Finally, data was collected for maximum and mean angles based on the entirety of the obstacle crossing session. Data was being collected during the natural walking patterns as well as during the obstacle crossings. Isolating the obstacle crossings to a “stance, cross, stance” window may show clearer data specifically targeting angle mechanics during the obstacle crossing phase.

Conclusion

The purpose of this study was to examine changes in lower extremity joint angles of the ankle, knee, and hip as a result of virtual reality obstacle crossing technology and feedback within the virtual environment. Virtual reality obstacle crossing training has been shown to translate to safer obstacle crossing strategies in the real world. The goal was to better understand how the safer obstacle crossings are achieved potentially as a result of biomechanics of the joints and/or feedback in the environment. My first hypothesis was that the no feedback group would not change their hip, knee, or ankle angles from pre- to post-training, which I found to be correct. This was majorly because participants would not know if they cleared the obstacle or contacted the obstacle with a specific part of their foot. Without feedback, they would be unlikely to change their biomechanics. I also hypothesized that I would see an increase in hip and knee angle flexion in the lead limb. There was a trend to support the opposite of this for the knee, but it was not significant. The hip data confirmed this hypothesis true as it was significant. Finally, the angle showed no significance and large standard deviations. If the sample size is increased, more trends and more significant data may be discovered.

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