Haptic Proprioception in a Virtual Locomotor Task

Kiran Karunakaran, Kevin Abbruzzese, Hao Xu, Naphtaly Ehrenberg and Richard Foulds

***Abstract* — Normal gait needs both proprioceptive and visual feedback to the nervous system to effectively control the rhythmicity of motor movement. Current pre-programmed exoskeletons provide only visual feedback with no user control over the foot trajectory. We propose an intuitive controller where hand trajectories are mapped to control contralateral foot movement. Our study shows that proprioceptive feedback provided to the users hand in addition to visual feedback result in better control during virtual ambulation than visual feedback alone. Hand trajectories resembled normal foot trajectories when both proprioceptive and visual feedback was present. Our study concludes that haptic feedback is essential for both temporal and spatial aspects of motor control in rhythmic movements.**

I. INTRODUCTION

Individuals with paraplegia due to spinal cord injury (SCI) have impairment to their motor and sensory feedback systems in their lower extremity often resulting in the inability to walk. Although wheelchairs provide mobility, they are limited in their ability to support everyday activities [1, 2]. Current research tries to address the issue of ambulation through wearable exoskeletons. Two exoskeletons have been developed and are currently available in the market: the Ekso and the Rewalk. Both exoskeletons have preprogrammed gait [2, 3]. The user can initiate the movement but has little control over the stride length or amplitude of the step. A limitation of these exoskeletons concerns the lack of control of the gait cycle. Current exoskeletons only provide visual feedback and lack sensory input related to force feedback, as most users have impaired lower extremity sensory system. In order to build a more intuitive control system, we propose that hand trajectories and finger trajectories can be applied to control foot trajectory [4]. In this study, we map hand trajectories to foot trajectories in a virtual environment to validate the need for the use of both haptic and visual feedback for effective control of an exoskeleton.

Upper extremity studies have shown that combining visual and haptic feedback leads to better performance than visual-only or haptic-only training. Feygin et al. concluded that spatial aspects improved with visual training while temporal aspects improved with haptic training [6]. Gunn et al. have shown that speed and accuracy improved in the upper extremity when haptic feedback was introduced along with visual feedback from a virtual environment [6]. Both studies suggest that combination of both haptic and visual feedback leads to better training.

Analysis of non-disabled subjects shows that both proprioceptive and visual feedback are present in the control of gait [7]. In the case of lower extremities, the basic tasks of walking, standing and balancing rely heavily on proprioceptive feedback mainly force and vestibular feedback. Force (haptic) feedback is essential to control rhythmic gait trajectories, while vestibular feedback is important for balance. Upper extremity control relies heavily on visual feedback for guidance while lower extremity control uses visual feedback for obstacle navigation through scans of the environment and does not control the gait pattern of each leg.

Koritnik et al. demonstrated that haptic-only mode provided better spatial and temporal adaptation than a visual only mode during rehabilitation of lower limb. Also, visual and haptic feedback can improve performance of lower extremity training than visual-only and haptic only mode [8]. Cowan et al. have shown that providing sensory feedback-like force impulse to the hand while performing rhythmic motor tasks, such as virtual paddle juggling, enhances performance by reducing variability in the rhythmic movement [9].

Rhythmic motor movement tasks like walking or juggling rely on haptic feedback to transition from one state of movement to another. These rhythmic movements utilize haptic feedback to convey information about the surrounding environment and body to control the timing of transitions. Human walking involves rhythmic behavior where haptic feedback is provided from heel strike to toe off. It is our hypothesis that to effectively develop an interface to control walking, haptic feedback must be provided to the nervous system to provide proprioception for each phase of gait to improve rhythmicity.

II. METHODS

A. Experimental Setup

18 subjects consented to participate in a virtual ambulation study approved by the Internal Review Board of NJIT. Subjects were positioned in front of a virtual environment center (VEC) that consisted of a

Research supported by Gustavus and Louise Pfeiffer Research Foundation and National Science Foundation Research Experience for Undergraduates (REU) (grant 1156916). Kiran Karunakaran, Kevin Abbruzzese, Hao Xu, Naphtaly Ehrenberg and Richard Foulds are with the New Jersey Institute of Technology, Newark, NJ 07102 USA

chair and monitor (Figure 1), Nest of Birds (NOB) electromagnetic position/orientation tracker (Ascension Technologies) to track the hand trajectories and two 3 DOF haptic devices (Geomagic Phantom Omni) to provide force feedback of 0.88 N. The NOB sensors were mounted to the Phantoms using a custom handle designed in Pro-E and fabricated by a 3D printer at NJIT. Each subject performed ambulatory trials in a virtual environment (VE) created in MATLAB using the Simulink 3D animation toolbox based on hand trajectories (Figure 2 A). The VE consisted of a pair of shoes on a virtual pathway (Figure 2 C). Positions for shoe movement were mapped from hand trajectories to allow real time ambulation in the VE. A black sheet was placed over the VEC and draped over the subject to cover hand movements and prevent references to devices.

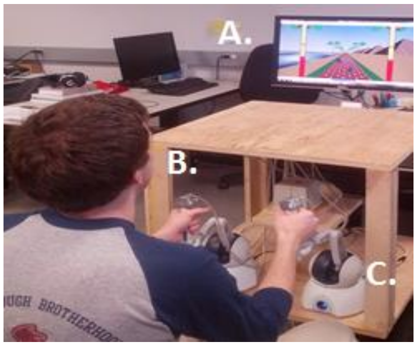

Figure 1: Experimental setup VEC. A) VE monitor. B) NOB sensor. C) Phantom Omnis.

B. *Experimental Procedure*

All subjects were non-disabled NJIT students with fully functional upper and lower extremities. Exclusion criteria included disability to upper or lower extremities or non-correctable visual impairment. All participants were randomly separated into three groups with six subjects each. Each group was classified based on the feedback: Visual, Haptic and Haptic & Visual. All subjects participated in five sessions where each session consisted of eleven trials of 60s ambulation followed by 60s of rest during which the controls were released. The first trial served as practice for each experimental group. Subjects were instructed to walk as far as possible during the trial duration. Experimental groups received visual feedback for their first trial. Both Haptic groups received both visual and haptic for the first trial. Each subsequent trial for the groups followed their respective protocol. Data analysis was performed only on trials two to eleven. The practice trial was omitted from data analysis.

All subjects were seated in a chair in front of the VEC and draped with a black sheet. Visual feedback from the VE consisted of shoes on a virtual pathway. Haptic surfaces were rendered to simulate force feedback from the pathway when the virtual shoes made contact with the virtual pathway. Vertical hand forces greater than the rendered forces of the pathway resulted in the shoe drop below the virtual pathway (fall throughs). The visual group performed trials with only visual feedback from the VE. Haptics were not rendered for this experimental group. Haptic group performed trials with only haptic feedback from Phantoms. The VE was not rendered on the monitor and subjects were asked to perform normal gait movements. Haptic &Visual feedback group received both types of feedback: visual and haptic. The VE was displayed on the monitor of the VEC to provide visual feedback. Haptic surfaces were rendered to simulate shoe collision on virtual pathway. Hand trajectories were mapped to contralateral shoe movement for all groups.

All subjects were asked to hold the Phantoms and perform gait-like movement using their hands. Movement would not occur if the shoe was below the virtual pathway or if both shoes were above the virtual pathway (Fig 2B). Ambulation would only occur if at least one shoe was resting on the virtual pathway. Stride length, amplitude and speed of shoes were controlled by the user's hand movement for all experimental groups.

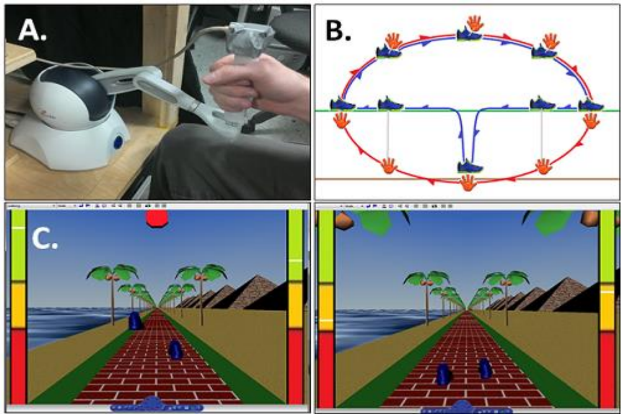

Figure 2: A) Phantom device with NOB sensor B) Typical virtual gait cycle: The shoe rises as the hand is elevated and the shoe is returned to the ground (green line) as the sensor reaches ground threshold: area between the green and orange line. The shoe drops below the virtual pathway when the hand goes below the orange line, which is known as fall throughs C) VE shoes and virtual pathway. The pathway acts as an infinite treadmill to allow forward progress of the shoe.

C. *Data Analysis*

MATLAB was used to collect and analyze the hand trajectory data from the NOB and to evaluate the performance of subjects. Horizontal and vertical trajectories were collected and analyzed to determine the time and amplitude synchrony. Distance traveled and fall throughs were analyzed to assess performance of each group. Statistical analysis was performed using IBM SPSS statistics toolbox to determine differences between experimental groups and to observe if learning occurred between trials, sessions and groups.

III. RESULTS

A. *Horizontal and Vertical Trajectory:*

Stance phase and swing phase duty cycle of hand trajectories were computed for all groups from vertical trajectories (Figure 3). Haptic & Visual hand trajectories demonstrated a duty cycle of 40.9% during swing phase and 59.1% during stance phase, while Visual only feedback group demonstrated a duty cycle of 19% during swing phase and 81% during stance phase. The Haptic only feedback group showed duty cycle similar to Visual only group.

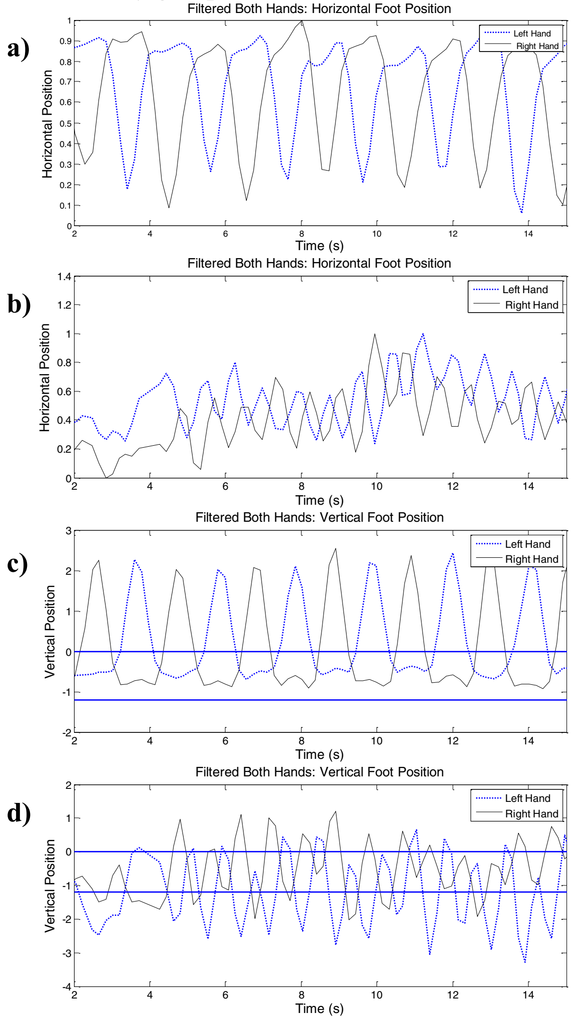

Figure 3: Horizontal Foot Position of a) Haptic &Visual feedback b) Visual only feedback . Vertical Foot Position of c) Haptic &Visual feedback d) Visual only feedback of subject 5 in session 5.

B. *Time Synchrony using Standard Deviation:*

The standard deviation between the inter-peak intervals for the horizontal trajectory of each hand was determined for each trial. An average of the standard deviation across trials for all subjects in each group for each session was computed. Figure 4, shows the average standard deviation of peaks between groups for each session. Kruskal- Wallis non-parametric test and Mann-Whitney *U* test with Bonferroni correction was performed to determine the statistical difference between the groups. Significant group differences were observed at $p<0.017$ between the three groups for both right and left hand.

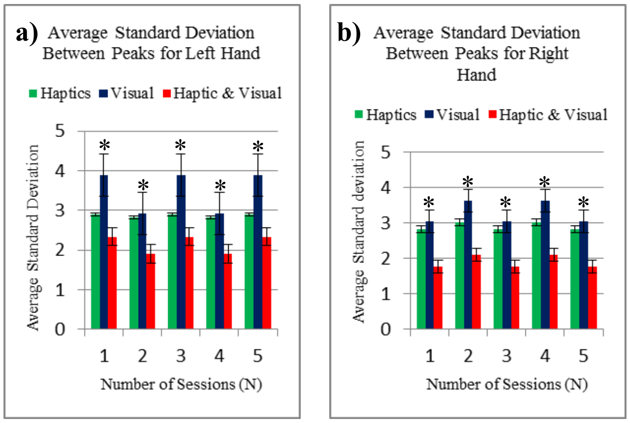

Figure 4: Average standard deviation between peaks for a) right hand b) left hand for each sessions. * represents significant difference between all groups

C. *Fall Throughs:*

The average fall throughs per unit distance across subjects for each session in each group was computed. Figure 5 shows average fall throughs for each session for all five sessions of the left hand. Kruskal-Wallis non-parametric test and Mann-Whitney *U* test with Bonferroni correction was performed to determine the statistical difference between the groups. Significant group differences were observed at $p<0.017$ between the three groups for left hand.

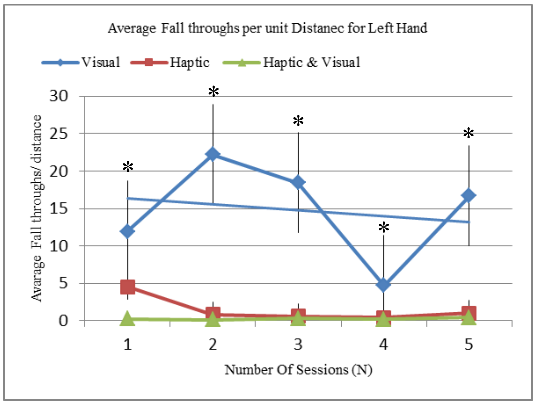

Figure 5: Average Fall throughs for each session. The linear fit for Visual only group indicates a decrease in fall throughs per session. * represents significant difference between all groups

D. *Distance Travelled:*

The average distance travelled for each session for each group was computed. Figure 6 shows the average distance travelled by each group for each session. One way Anova and Tukey's post hoc test were performed to determine the statistical difference between the groups. Significant difference were observed between Haptic & Visual group and Visual only group ($p<.05$) and Visual only and Haptic only group ($p<.05$) for both hands. No significant difference was observed between Haptic & Visual group and Haptic only group for both hands.

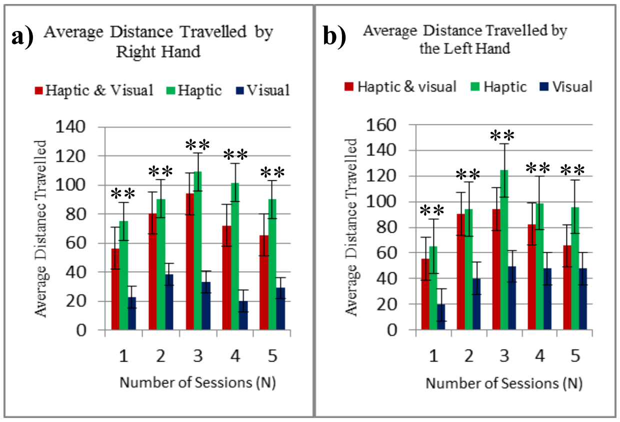

Figure 6: Average Distance travelled by a) right hand b) left hand. ** represents significant difference between visual only and haptic only group and visual only and haptic &visual group.

IV. DISCUSSION

Our results show that Haptic & Visual feedback group has better time and amplitude synchrony. Figure 3 shows that when one hand is in stance phase the other is in swing phase as observed during normal gait cycle in Haptic & Visual feedback group. Normal gait cycle is divided into two phases: swing and stance. Swing Phase occupies 40% of gait cycle and stance phase occupies 60% of gait cycle respectively [10]. Our analysis of the Haptic & Visual hand trajectories demonstrate a duty cycle of 40.9% during swing phase and 59.1% during stance phase. Hand trajectories of Visual only feedback group demonstrated a duty cycle of 19% during swing phase and duty cycle of 81% during stance phase. This indicates that hand trajectory from Haptic & Visual feedback group mimic natural gait trajectory.

The standard deviation between the peaks of the horizontal trajectory was used as a measure to evaluate the time synchrony. A low standard deviation between the peaks signifies synchrony. Figure 4 shows Haptic & Visual feedback group have lower standard deviation than both Visual only and Haptic only groups. This signifies greater synchronicity in Haptic & Visual group compared to the other two groups. The Haptic only group showed better synchrony than the visual only group. Our findings are in accordance with Turchet et al. that haptic feedback plays a relevant role in the perception of both real and simulated surfaces during the act of walking [11]. This indicates haptic feedback is essential for motor control of rhythmic movement.

The error in amplitude synchrony was quantified by the number fall throughs. Figure 4 shows the average fall throughs per unit distance. Haptic & visual feedback group had fewer fall throughs compared to the other groups. This group displayed better spatial awareness and was able to estimate the position of the shoes on the Virtual Pathway. Haptic only group had fewer fall throughs compared to Visual only group, implying haptic feedback is important in spatial awareness in ambulation. In session 4, subject 4 in Visual only group displayed less fall throughs per unit distance compared to all other Visual only subjects. This reduced the mean as observed in Figure 5. The fall throughs per unit distance across sessions show that there is no significant change in learning after session 2.

Distance travelled by the Haptic only and Haptic & Visual feedback groups were significantly better than Visual only group. This implies Visual only feedback does not play a role in virtual horizontal movement.

V. CONCLUSION

Both haptic and visual feedback is vital for the synchronicity of amplitude trajectory during the normal gait cycle. Haptics is essential for synchronicity in horizontal trajectory and spatial awareness.

Our study concludes that haptic feedback is essential for both temporal and spatial aspects of motor control in rhythmic movements. Hence, an alternative control mechanism for gait should involve haptic feedback to allow the user to control stride length or amplitude of the step and maintain the motor rhythmicity with proprioception.

ACKNOWLEDGMENT

The authors thank Isaac DuPree, Eric Apgar and Luis Morales for their work during the NSF Research Experience for Undergraduates Program at NJIT.

REFERENCES

1. Ditunno, P.L. , Patrick, M, Stineman, M, Ditunno, J.F. Who wants to walk?Preferences for recovery after SCI: a longitudinal and cross section study. Spinal Cord 2008,467),500-6.
2. Esquenazi, Alberto, et al. "The ReWalk Powered Exoskeleton to Restore Ambulatory Function to Individuals with Thoracic-Level Motor-Complete Spinal Cord Injury." American Journal of Physical Medicine & Rehabilitation (2012).
3. Strickland, Eliza. "Good-bye, wheelchair." Spectrum, IEEE 49.1 (2012): 30-32.
4. Kiran K Karunakaran, R.F., Control of Foot Trajectory in Biped Robots. 39th Annual Northeast Bioengineering Conference (NEBEC), 2013: p. 203-204.
5. Feygin D, K. M., Tendick F (2002). "Haptic guidance:experimental evaluation of a haptic training method for a perceptual motor skill." Proceedings of the 2002 symposium on haptic interface for virtual environment and teleoperator systems (HAPTICS'02): 40-47.
6. Gunn C, M. W., Datta A (2009). "Performance improvement with haptic assistance: A quantitative assessment." Proceedings of 2009 joint Eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems: 511-516.
7. Haas B (2010) 'Motor Control' in Everett T; Kell C (ed.) Human Movement Edinburgh: Churchill Livingstone pp 47 - 60
8. Koritnik, T., et al. (2010). "Comparison of visual and haptic feedback during training of lower extremities." Gait Posture 32(4): 540-546.
9. Ankarali, M.M., et al., Haptic Feedback Enhances Rhythmic Motor Control By Reducing Variability, Not Convergence Rate. J Neurophysiol, 2013.
10. Winter, D., Biomechanics and motor control of human movement. 2005.
11. Luca Turchet, P.B., and Stefania Serafin, Haptic Feedback for Enhancing Realism of Walking Simulations. IEEE TRANSACTIONS ON HAPTICS, 2013.