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Light touch based virtual cane for balance assistance during standing

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LIGHT TOUCH BASED VIRTUAL CANE FOR BALANCE ASSISTANCE DURING STANDING

by

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ABSTRACT

Can additional information about one's body kinematics provided through hands improve human balance? Light-Touch (LT) through hands helps improve balance in a wide range of populations, both healthy and impaired. The force is too small to provide any meaningful mechanical assistance – rather, it is suggested that the additional sensory information through hands helps the body improve balance.

To investigate the potential for improving human balance through biofeedback through hands, we developed a Virtual Cane (VC) for balance assistance during standing. The VC mimics the physical cane's function of providing information about one's body in space. Balance experiments on 10 healthy young adults are conducted, where the evidence of improved standing balance with VC is collected and analyzed in terms of both, medio-lateral & anterior-posterior accelerations of the trunk. The results showed that VC improved balance in both X & Y directions as compared to no cane and in some cases, balance improvement was almost as good as physical cane condition. This shows that standing balance can be improved by even a simple binary information on one's hand position with respect to the ground.

This work furthers the concept of biofeedback from using virtual devices for balance assistance - using virtual LT through hands. Specifically, this work investigates a novel case where information that otherwise cannot be provided by any of the sensory organs (i.e., accurate distance from one's hand to an external object), improves human standing balance. This research will propagate and give a boost to inspect and analyze similar or supplementary improvement effects during walking.

ACKNOWLEDGEMENTS

First, and most of all, I would like to gratefully acknowledge my advisor, Dr. Yun Seong Song, for his persistent counsel and support. I'm extremely thankful for his belief in me and his thoughtful encouragement and careful supervision. I really appreciate the assistantship rendered by him and shall always be indebted. I never would've seen myself presenting in International conferences and I only have him to thank for such great opportunities and exposure. Many thanks to Dr. Frank Liou and Dr. Devin Burns, for graciously agreeing to be in my committee and providing me with their valuable time and insights, which proved to be truly thought provoking. I would also, like to extend my thanks to Vincent Marco and Darian Emmett, for their collaboration with prototype development and coding. Finally, yet importantly, I would like to smile on Anirudh Saini, my boon companion, and my beloved family, for helping me in every step of my research journey.

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1. INTRODUCTION

Falls are the second leading cause of accidental or unintentional injury deaths worldwide, where each year an estimated 646,000 individuals die from falls globally according to World Health Organization (WHO) [1]. A better balance during walking can mitigate falls, which occur mostly during locomotion [2 - 4], and are one of the major causes of life-threatening injuries in older adults [5, 6]. Assistive devices such as canes (standard, offset, quadripod); crutches (axillary, forearm, platform), or walkers (standard, front-wheeled, four-wheeled) can help improve balance during standing, especially for populations who require high-force physical assistance.

However, for people who are still physically capable yet suffer slightly reduced balance, there are notable drawbacks in using these devices for everyday use. For example, these devices occupy the hand(s) of the user, thereby reducing the dexterity of their arms and are often bothersome to carry around. In addition, these devices may induce social stigma by openly presenting the disability of the user. Also, reduced usage of weak yet functional muscles due to canes or walkers may prevent recovery and accelerate dependence on these assistive devices.

Light interaction forces may help improve balance while allowing the user to use their functional muscles. In biomechanics, the ability of Light Touch (LT) to drastically improve human balance has received wide attention. Unlike using physical assistances, it was first shown by Jeka in 1994 [7] that, light contact of the fingertip on a rigid surface was enough to drastically reduce the Center-of-Pressure (CoP) sway of healthy individuals during quiet standing. That is, a simple application of such a small force onto one of the most distal part of human body (fingertip) was sufficient for the human participant to outperform his/her own best effort to stand as still as possible. The force is too small to provide any meaningful physical assistance – rather, it is suggested that the additional sensory information provided through LT helps the body improve balance under its own power. Hence, it is generally agreed that the proprioceptive sensory information from LT, and not the mechanical support provided by the reaction forces, helps improve human balance. For the mechanical torque from the reaction force by LT to be large enough to affect the balance, the reaction force magnitude must be over 4 N, which is at least four times greater than the force typically provided by LT [7]. Instead, LT may provide sensory information, especially when it is reduced due to mobility impairment [8] or aging [9]. Indeed, modulating the touch location, but not touch magnitude, resulted in the modulation of the CoP during standing, even when the human subjects were not aware of such modulation in place [10, 11] – which suggests a strong coupling between the sensory information from LT and human standing balance. Similar improvement in standing balance using LT was observed in a wide range population, further testifying the dramatic balance improvement (in healthy young adults [7, 12], healthy older adults [9], stroke patients [13, 14], peripheral neuropathy patients [15], Parkinson's Disease patients [16] and anterior cruciate ligament (ACL) injury patients [8]).

Shima [11] proposed a novel concept of virtual light touch contact, where the information about the position of one's body, provided through vibrations and not through force, was capable of increasing standing balance. According to Beek [17], step width of the subjects significantly decreased during treadmill walking with light touch on the handrail. These imply that, the somatosensory information provided through LT or virtual LT help improve body balance even without physical assistance.

These remarkable results revealed the potential for using LT for human balance assistance without providing mechanical assistance – through providing sensory augmentation. The reaction force provided by LT is too small to provide mechanical support [7, 10, 18, 19]. Instead, it is widely accepted (but not explicitly shown) that the proprioceptive sensory information from LT is what helps improve standing balance. Our goal is to bring the benefit of LT out of the lab and into the everyday lives of people who could benefit from standing assistance and fall prevention. Above mentioned studies motivated us to further contemplate on removing all contact and investigate regarding the usage of virtual light touch contact to improve standing balance, with a wearable device that is subtly hidden from view. The outcome is an effective and affordable standing balance assistance system that can also reduce social stigma and reluctance to use assistive devices due to their appearances [18].

This interdisciplinary research aims to reduce the risk of falls in frail populations by developing and evaluating a novel wearable balance assistive device inspired by virtual Light-Touch (LT), named the Virtual Cane (VC). The long-term goal is to extend the evaluation to frail populations such as older adults or people who regularly use walking aids. People requiring assistance during walking, often use an object of their own, such as a cane or a crutch, and maintain contact with the object throughout walking. While the physical contact between a cane handle and the hand may not be considered LT, the contact of the cane to the ground and the subsequent sensory information through the hands could resemble LT. For example, one may choose to only lightly touch the ground with his/her cane, similar to how visually-impaired people use their canes for exploration. Indeed, if LT were providing information about the location of fixed external objects and therefore the information about one's body location, one does not have to make physical contact with an external surface to gain these benefits. Rather, simulated LT could simply inform the user of the distance between his/her body and an external object or the ground itself. With these considerations, our VC is the one that functions like a cane without the mechanical support, but with the information about the distance. That is, the instrumented VC mimics the physical cane on the information provided by it – the distance between an external object/ground to the subject, therefore acting like a virtual cane of fixed length, and inform the user through cutaneous senses.

Our hypothesis is that, balance improvement can be found in healthy, young adults by utilizing information provided through virtual light touch, i.e., vibration feedback at fingertips, administered by our assistive device.

2. METHODS

2.1. APPARATUS

The VC was designed to allow the testing of above-mentioned hypothesis such that it is capable of delivering information through fingertips and assist in improving human body balance. In this view, the VC should feel like a physical cane in its weight and inertia, except for the sensation of contact to the ground. To ensure as similar mechanical feel as possible, we accommodated VC apparatus with a trifold cane that measures the distance between the cane and the ground and a glove that provides this information to the user in the form of vibration. The trifold, physical cane (5 cm × 18 cm × 33 cm), as shown in Figure 2.1, is height adjustable (83 cm ~ 93 cm). At about 21 centimeters from the bottom of the shaft of the physical cane, an Ultrasonic sensor (HC-SR04; ranging distance of 2 cm ~ 500 cm and resolution of 0.3 cm) is mounted. This is used to measure the real-time distance of the cane from the ground, which gives feedback to the vibration actuators if the change in distance is more than 5 cm. It is also equipped with an Arduino UNO microcontroller to oversee the operation of sensors and actuators. The glove, as shown in Figure 2.2, consists of three bend sensors/ short flex sensors (P1710; flat resistance of 25K Ω) and four vibration actuators (P1201A; 2V ~ 5V). Bend sensors are placed along the thumb, middle finger and little finger of the glove, and are used to detect if the hand is making a grip while holding the cane. Vibration actuators propped on the outer side of the glove at fingertips of all except middle finger, to provide the distance information to the wearer. This is how, the VC mimics the physical cane's function of providing information about one's body in space.

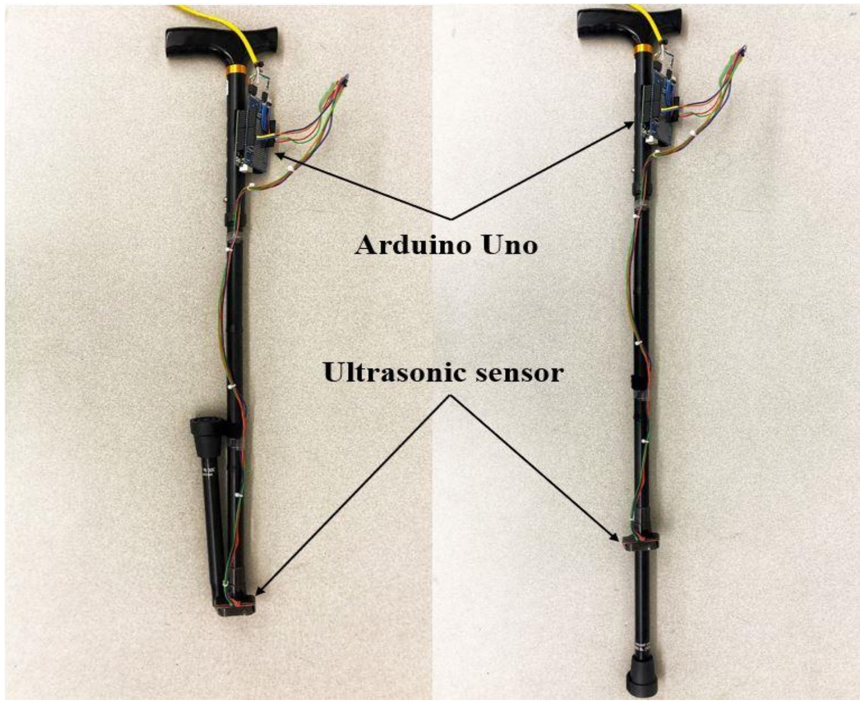

Figure 2.1. (Left) Folded and (right) unfolded physical cane with an Arduino Uno at the handle and an ultrasonic sensor at the bottom fold of the cane's shaft.

Figure 2.2. (Left) Outer side of the glove with bend sensors on thumb, middle and little fingers. (right) Inner side of the glove with vibration actuators on all except middle finger.

Figure 2.3 depicts a subject in tandem stance, right foot front, eyes closed, barefoot on the axis at the center of a force plate (Optima OPT400600HF, Advanced Material Technology Inc.), with the VC setup i.e., a glove on his right hand while holding the trifold, physical cane. The force plate measures the medio-lateral Center of Pressure (CoP_x) and the anterior-posterior (CoP_y) from the force components (F_x, F_y and F_z) of the active forces applied to its surface, which are used to calculate the center-of-pressure (CoP) of the subject.

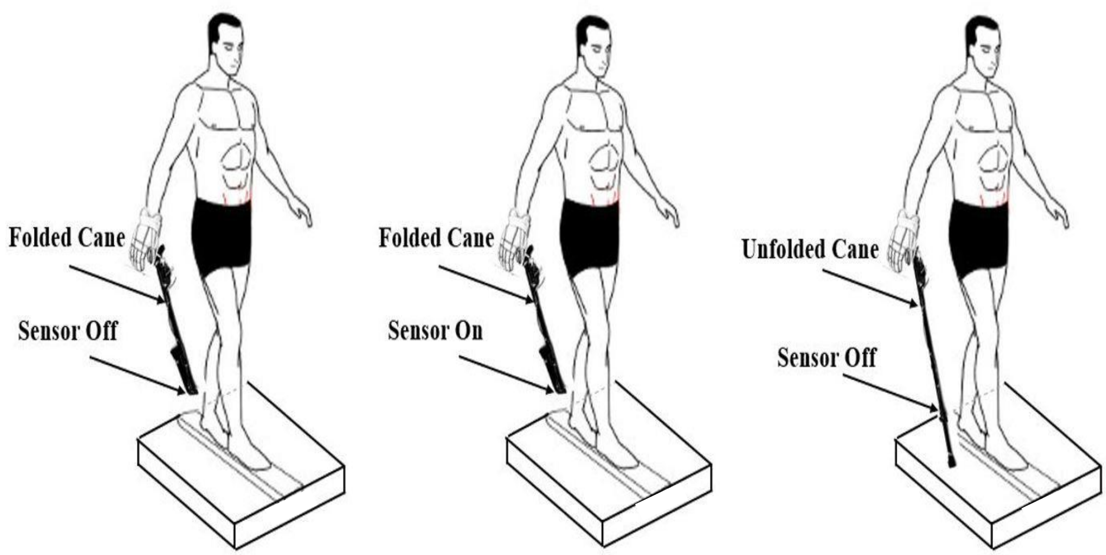

Figure 2.3. Subject standing on the force plate in tandem stance, with eyes closed, right foot in front of the left in three control conditions. a) No Cane, b) Virtual Cane and c) Physical Cane.

2.2. PARTICIPANTS

Human balance assistance experiments, through sensory augmentation, approved by the Missouri S&T Institutional Review Board (IRB), were conducted on ten participants, who volunteered for the study and have given written consent forms, prior to the experiment. Among the individuals participated, there were five men and five women, with their ages ranging from 19 to 30 years. All the participants were physically active and healthy with no known neurological disorders or musculoskeletal injuries, which might affect their balance maintaining ability.

2.3. PROCEDURE

Initially, the subject was acquainted with the IRB approved form and after taking their consent, they were made aware of the tandem stance and were given two minutes to practice it in an eyes closed condition. The subject was instructed to stand, as quietly and still as possible, on the anterior-posterior axis of the force plate with their eyes closed, bare foot, in tandem stance, right foot first [24], under three conditions.

i. No Cane (NC) – In this condition, the participant was standing on the force plate in the above-mentioned stance. In the right hand, at any comfortable height, they were holding the cane, whose bottom quarter of the shaft is folded. This ensures the mechanical grip and sense of the physical cane, without giving ground support. The other hand rests freely. Also, no vibration feedback was given to the actuators on subject’s hand glove. Even though this could be done with an idle stance, the participant was made to stand holding the cane to standardize the body position in all three control conditions.

ii. Virtual Cane (VC) – In this condition, the cane remained folded, but the glove was powered on and the participant was asked to point the cane with the ultrasonic sensor onto the force plate. This ensured no physical assistance and only biofeedback. Whenever their deviation from the comfortable height exceeded a specified limit of 2.5 cm in either direction (providing 5 cm thickness of no vibration zone), feedback was provided to the participant's finger tips through vibration actuators. The amplitude of the vibration was fixed and did not depend on the measured distance from the sensor.

iii. Physical Cane (PC) – In this condition, the glove was powered off and the participant was given physical support by resting the end of the unfolded cane shaft on the force plate. The participants were free to exhibit their desired amount of force through the cane, as they would with any ordinary cane.

Enough time was given to the participant to get comfortable in their stance on the force plate and to be as still as possible for the entire trial. The trial began only when the participants felt stable enough and said 'ready' or 'go'. Each participant performed three blocks of experiments with 12 trials each, with four of each condition per block and all the three conditions randomized in each block. The duration of each trial was 20 seconds. A 5-minute break was given to the participant after each block of trials. To ensure the same feet position in all the trials for all participants, anterior-posterior axis was marked on the center of the force plate using adhesive tape.

2.4. ANALYSIS

Data from blocks 1 & 2 were not taken into account, to rule out any possible learning effect. The third blocks of all 10 participants were analyzed using MATLAB (MathWorks) to derive CoP values at any given point of time during the trial. From these values, standing balance was measured in terms of the standard deviations of CoP as well as the standard deviations of velocities of CoP. First, we found the CoP data from the force plate such that

$$CoP_x = -\frac{(M_y + F_x * t)}{F_z} \quad (1)$$

$$CoP_y = \frac{(M_x + F_y * t)}{F_z} \quad (2)$$

where, *t* is force plate thickness. Velocities of CoP_x and CoP_y are calculated by differentiating their moving means in both directions and multiplying them with sampling frequency (F_s = 1 kHz). The standard deviations of CoP_x (*SD* CoP_x) and that of CoP_y (*SD* CoP_y), as well as the standard deviations of the velocities of CoP in x (*SD* $vCoP_x$) and y direction (*SD* $vCoP_y$) were then found. These balance metrics were then analyzed using ANOVA in SPSS (IBM).

3. RESULTS

The Mean values and Standard errors of *SD CoP* and *SD vCoP* in both X and Y directions, of all 10 participants, under three conditions, are shown in Table 3.1.

Table 3.1. Mean and Standard Error.

Condition	***SDCoPx***		***SDCoPy***		***SDvCoPx***		***SDvCoPy***	
	Mean	***Std. Error***	***Mean***	***Std. Error***	***Mean***	***Std. Error***	***Mean***	***Std. Error***
NC	10.27	0.84	7.70	0.98	45.47	4.07	41.09	5.98
VC	8.79	0.60	6.16	0.71	40.53	2.96	31.84	3.54
PC	8.54	0.68	5.99	0.90	29.38	2.45	21.61	2.50

From the above table, the means of Standard deviations of CoPs and Standard deviations of velocities of CoPs in both anterior-posterior and medio-lateral directions, show a decreasing trend from NC to PC, implying improved balance using the physical cane as expected. In addition, there is a clear improvement in all the metrics from NC to VC, in both directions.

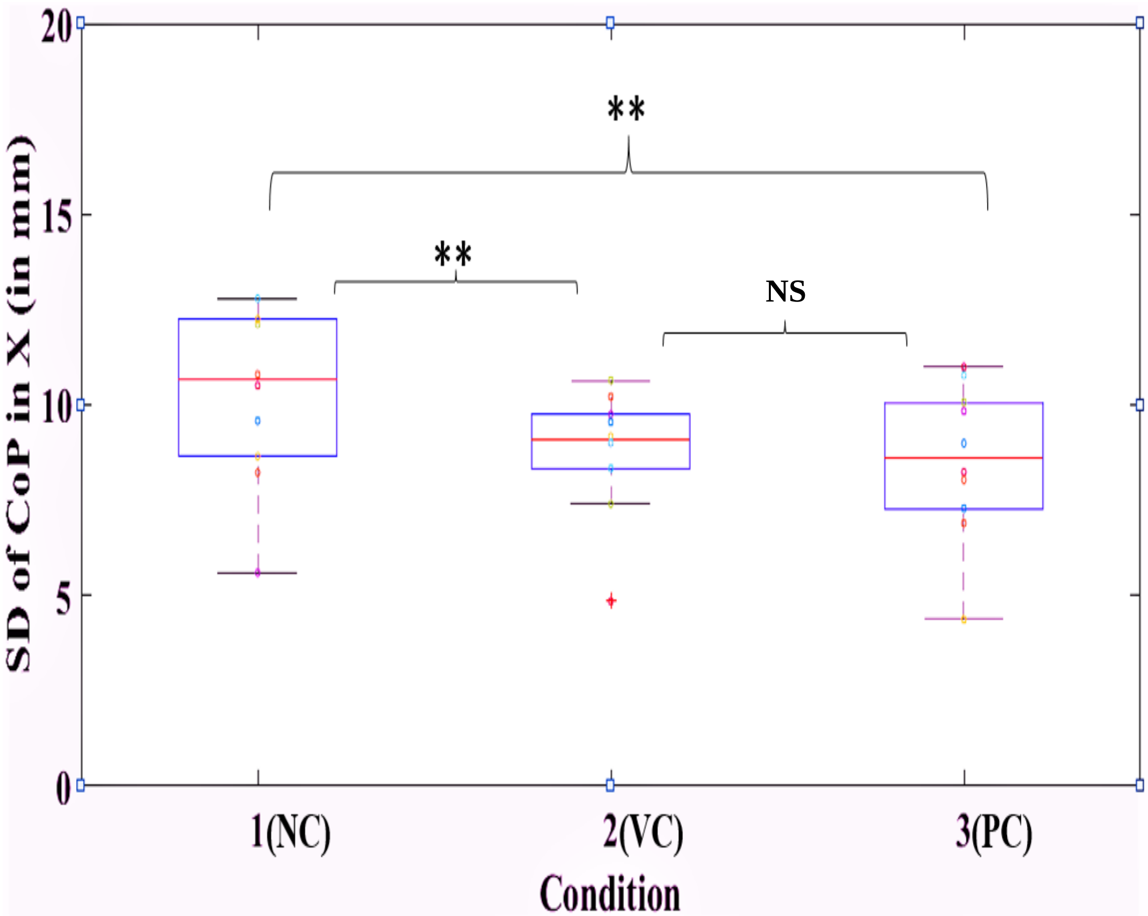

Figure 3.1. Standard Deviation of CoP of all subjects in X direction under three control conditions – No Cane (NC), Virtual Cane (VC) and Physical Cane (PC). ** denotes 'high significance' and NS denotes 'no significance'.

In Figure 3.1, there is visible decrease of *SD* CoP_x from NC to PC with a significance of p<0.001. The metric showed a decrease from NC to VC with a significance of p<0.001. Even though, there is a decrease from VC to PC, it is not significant with the value being p=0.728. This implies that, there is significant improvement in standing balance from NC to VC but, no significant improvement from VC to PC, in terms of *SD* CoP_x.

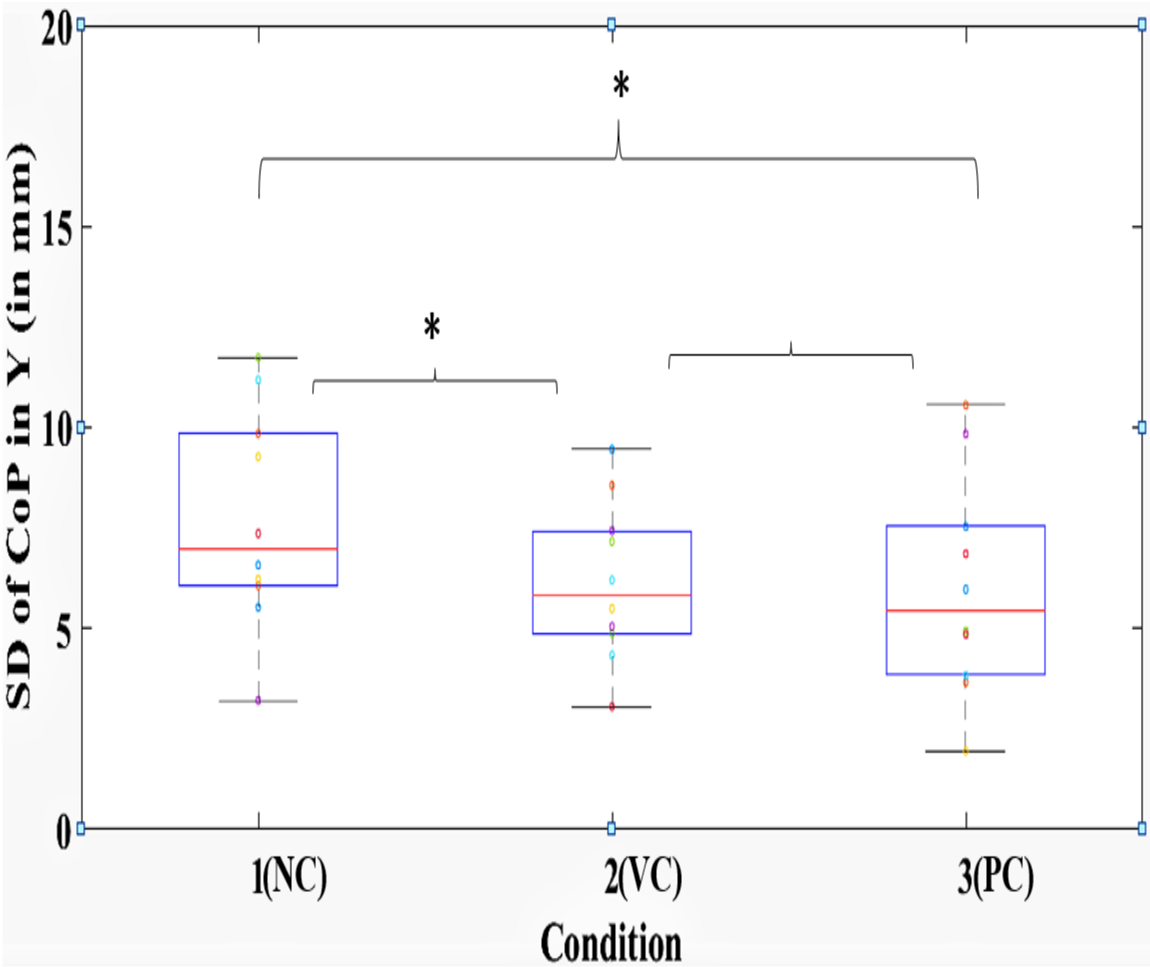

Figure 3.2. Standard Deviation of CoP of all subjects in Y direction under three control conditions – No Cane (NC), Virtual Cane (VC) and Physical Cane (PC). * denotes ‘significance’ and NS denotes ‘no significance’.

In Figure 3.2, there is visible improvement of *SD* CoP_y from NC to PC with a significance of p=0.019. The metric showed a decrease from NC to VC with a significance of p=0.038. Even though, there is a decrease from VC to PC, it is not significant with the value being p=0.962. This implies that, there is significant improvement in standing balance from NC to VC and no significant improvement from VC to PC.

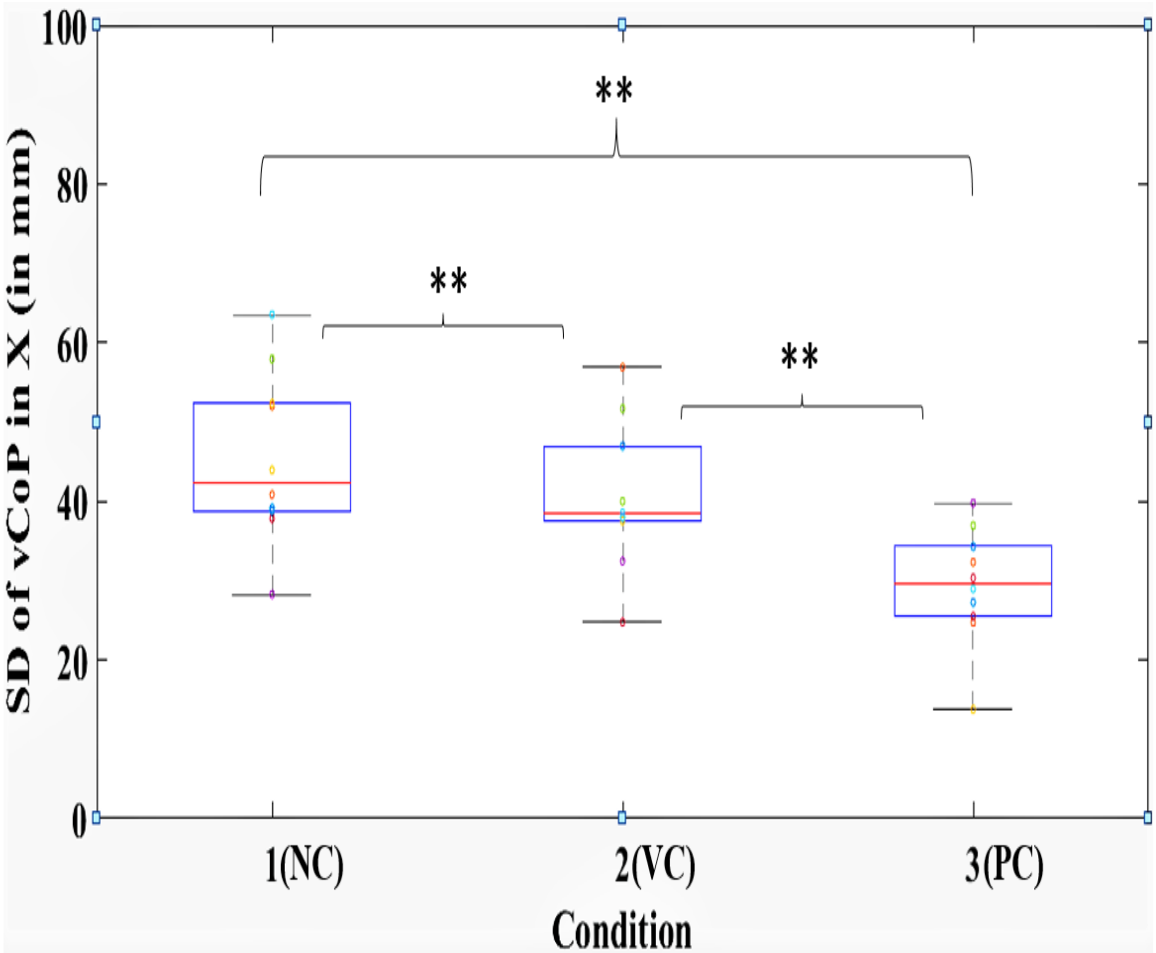

Figure 3.3. Standard Deviation of vCoP of all subjects in X direction under three control conditions – No Cane (NC), Virtual Cane (VC) and Physical Cane (PC). ** denotes ‘high significance’.

In Figure 3.3, there is visible improvement of *SD* $vCoP_x$ from NC to PC with a significance of $p<0.001$. The metric also showed a decrease from NC to VC and VC to PC with a significance of $p<0.001$. This implies that, there is significant improvement in standing balance from NC to VC and also from VC to PC.

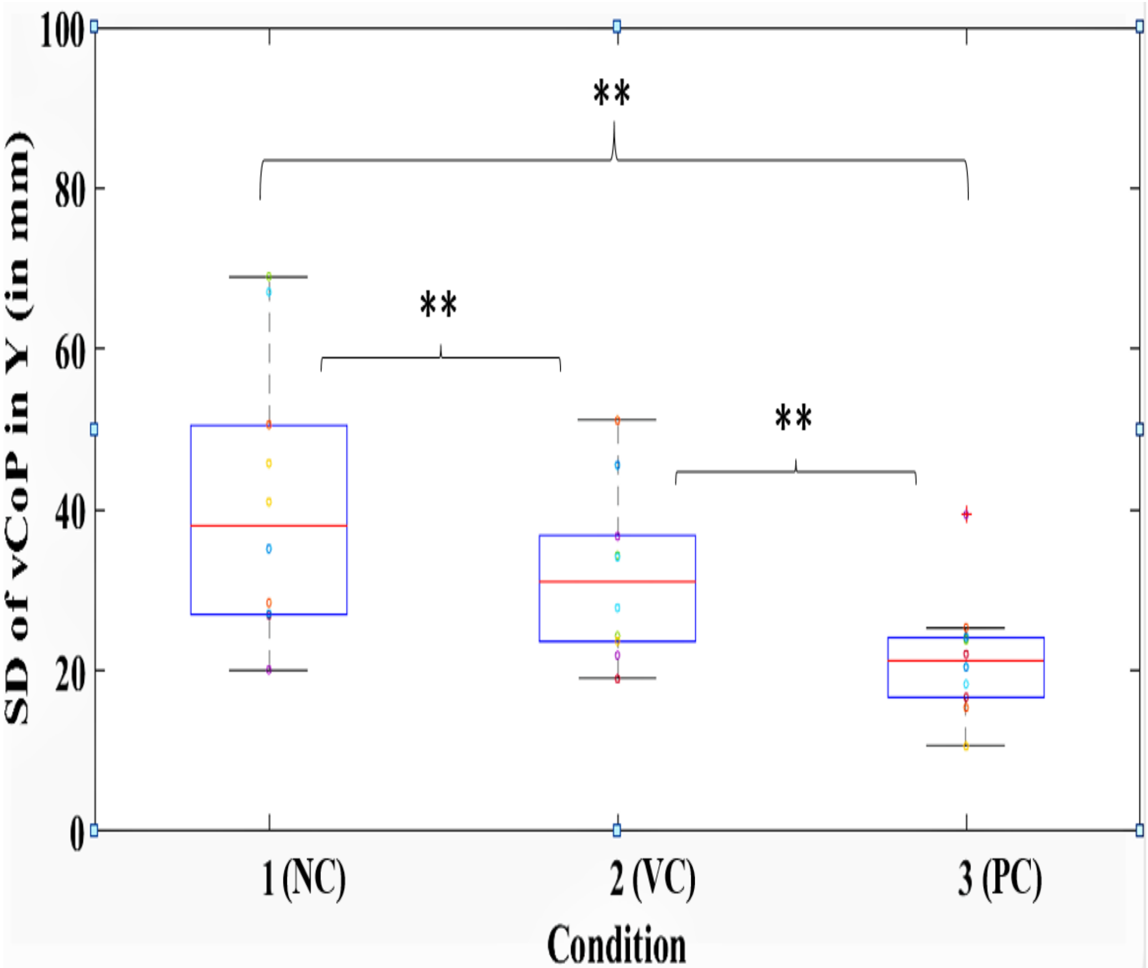

Figure 3.4. Standard Deviation of vCoP of all subjects in Y direction under three control conditions – No Cane (NC), Virtual Cane (VC) and Physical Cane (PC). ** denotes 'high significance'.

In Figure 3.4, there is visible improvement of *SD vCoP*$_y$ from NC to PC with a significance of $p<0.001$. The metric also showed a decrease from NC to VC and VC to PC with a significance of $p<0.001$. This implies that, there is significant improvement in standing balance from NC to VC and also from VC to PC.

Key takeaways from the above results are:

- VC improved balance as much as PC did, according to Standard Deviation of CoP in both, X & Y directions.
- When Standard Deviation of *vCoP* in X & Y directions is considered, PC is best but there is significant improvement in VC when compared to NC.

4. DISCUSSION

Contrary to prior studies, in the current experiment there is no physical force used at all in VC condition. This is a first of its kind and it is intriguing to contemplate more possibilities of developing extended auxiliary balance assistive devices in the future.

In the early stages of prototype development, instead of ultrasonic sensors, infrared sensors were employed and VC was tested. Due to high interference and low reliability, even in moderately lit environment, we later switched to ultrasonic sensors. Also, the vibration actuators were planted on the outer side of the fingers of the glove, during pilot experiments. However, after considering the fact that inner tips of the fingers are more sensitive than finger nails, their position is switched. Moreover, there was no physical cane in our initial approach. Instead, there was only a handle on which ultrasonic sensor was mounted and pilot experiments were conducted under only two control conditions. One, with idle bipedal stance and the other, with the glove and the handle. There might have been an effect of difference in body postures on the body sway. In order to eliminate that and standardize the body posture, in all control conditions and to precisely know the relative amount of improvement, physical cane is implemented under all control conditions. In these initial pilot experiments, subjects were standing on the force plate in idle bipedal stance, with their eyes closed, and the body sway was found too small for these healthy, young adults, to compare under two control conditions. Therefore, to make it more arduous, we changed the stance from bipedal to tandem [7, 23], which is a widely used means of increasing the difficulty in medio-lateral direction. Considering the fluctuations of the distance when the user points the cane at any desired angle, all the subjects were made to point it on to an area marked on the force plate.

Although, according to many earlier studies, it is suggested that the information (and not the mechanical support) LT's may help improve balance, this potentially important hypothesis was not explicitly tested. This may have been due to the fact that, testing such idea requires a special setup like the VC, that ensures only information transfer and no mechanical contact. And, so forth, these results evidently show that no physical assistance and only LT through vibration feedback, helps improves balance in healthy young adults. This discovery can be utilized in building new balance assistive devices and thus help in forming new therapy approaches that focuses on providing useful sensory information.

From the above results, it is observed that assistance from VC improves standard deviation of Centre of Pressure as much as PC does, but not on standard deviation of velocity of Centre of Pressure. This may be due to the fact that the position information (distance from cane shaft to the force plate) was provided for the biofeedback and not velocity information. This entails that, if we have provided other means of feedback that affects velocity, then it may have improved the *SD vCoP* measure of balance as well. In a recent study [25] conducted here at Missouri S&T, a haptic robot was used to investigate the information embedded in LT that improves standing balance in healthy young adults. It was revealed that, despite the additional positional information provided, significant balance improvement was mainly velocity-dependent, which is quite on the contrary of this work. Hence, the combined results of these two studies suggests a possible 'orthogonal' mechanism of standing balance modulation within human body – one responding to velocity information, and another to position information. Also, when it comes to the metrics in the current work, even though there are contemporary choices like the Mean

Sway Amplitude (MSA), shrewdly, *SD CoP* and *SD vCoP* are considered, thereby allowing us to scrutinize their respective effects on body balance.

There are a few reasons to choose trifold cane for our experiment. First one being the similarity with the typical physical cane. We wanted VC control condition to be as similar to PC as possible in all sensations, except for the information being provided. This eliminates effects of other factors, such as varying hand grip, weight, inertia etc. on the results. These may not affect balance, but since the effect of such factors on balance was never explicitly studied in the literature, we eliminated as much as possible the variations on these factors across all the control conditions. Secondly, Ultrasonic sensor provides more accurate measure of distance at a close range, so it was attached to the shaft of the cane at the end of second fold, so that we can work it with the minimum possible distance. Thirdly, for all the participants, we wanted to ensure that the VC points on to the force plate. Because the end of the folded cane was only roughly 20 cm away from the force plate, it was straightforward for the experimenter to determine if the VC pointed to the force plate or not. Therefore, a trifold physical cane proved to be an adequate design choice for this particular requirement.

Our current VC prototype provides distance information from the force plate to the cane, in both upward and downward directions. The information is binary in that it either turns on or turns off the vibration actuators on the glove. The vibration intensity is fixed and not modulated in any other way. Since it is assumed that no other form of information is being provided differently in comparison with all three control conditions, it therefore minimizes all the other factors that might affect balance results. More importantly, this binary information is the lowest form of information (1-bit), meaning that you can’t be less specific in the information provided. But even with such low resolution information, the participants' standing balance improved This result suggests that low-cost, low-resolution sensors may be sufficient for use in assistive devices. This also suggests that balance therapy programs may not have to commit to providing exact sensory information to the patient. This further implies that the brain may not require a high-resolution information to improve balance. The brain may prefer high-contrast, low-entropy binary information to make rapid decisions on how to maintain balance – a time-sensitive and critical task to avoid falls.

Although our results are promising for standing balance assistance, it may apply differently to other population or in other balance conditions. As mentioned earlier, all 10 participants on whom these experiments are conducted are healthy young adults, who may not rely much on physical cane for assistance. On this account, our VC may have stronger rehabilitation potential when it is used by people with stability disorder due to reduced sensory input. Additionally, the subjects were made to stand with their eyes closed to increase the level of difficulty for healthy young adults. Whether this experimental setup affected the level of effectiveness of VC is still unknown. For example, it may be argued that the increased difficulty led the participants to depend more on the information provided by VC. Also, it is unclear how the improvement in standing balance may translate to walking balance. The dynamic nature of walking described as a series of falls and catches with large CoP movement makes it difficult to generalize studies in standing balance over to walking [31, 32]. Indeed, even the metrics of balance are different from standing to walking [7, 11, 13, 17]. How to test the effect of VC in walking remains to be a challenging task for future research.

Nonetheless, our ultimate goal is to bring balance assistance out from the research lab and into more practical daily tasks, such as during walking. Indeed, despite evidence that standing balance is not related to walking balance [31, 32], LT has resulted in improvements both in standing balance and during walking (with a 7-meter walk with an instrumented cane [13], or on a treadmill with LT-handrail [33]). These studies point to the potential for utilizing LT for improving walking balance – an underexplored possibility that can lead to a great benefit. Even though we included the physical cane in our experiment, our work opens doors for possible outdoor balance assistive devices without any physical cane – and only with the glove with a sensor. The inclusion of the physical cane in the control conditions was to standardize the body posture in the experiment and need not be embodied in actual usage. The current glove prototype is already portable and can be used anywhere, hence making it convenient to extend this concept to walking. Future experiments involve analyzing human body balance improvement using VC during walking, with the help of gait mats, optical motion analysis [26], uniaxial [13, 30] or tri-axial accelerometer [27, 28, 29], Surface Electromyography [13, 17, 30], 3D motion capture technology [11], or foot switches [13, 27]. Building upon the result from this work, we are hopeful that low-cost walking balance assistance device that is information-based and hidden from view will be developed in the near future.

5. CONCLUSION

This work shows that, standing balance can be improved by information on one's hand position with respect to the ground and thus, takes a step beyond the traditional concept of biofeedback and explore the possibility of sensory augmentation for movement assistance. Instead of simply measuring and providing specific information that could have come from existing sensory organs in human body (ex. foot pressure [20, 21] or head orientation [22]), we explored LT to provide information that otherwise cannot be provided by any sensory organs – the accurate distance from one's hand to a physical object. This work can also be used to explore the possibility of using phantom sensation for movement assistance, such as the feel of an illusionary cane. In other words, this work can explore the full potential of the sensory capabilities of your body as a whole for improving awareness and mobility of the human body.

Our work will also impact the rapidly growing industry of Virtual Reality (VR) or Augmented Reality (AR). The sensory augmentation aspect of LT-based assistive devices can apply to VR or AR to provide a channel for virtual physical interaction and enhance the feel of authenticity. A novel rehabilitation scheme integrating LT and VR/AR can also be envisioned. In addition, our VC can provide amplified awareness to the surroundings, leading to applications such as intuitive navigation in low-visibility environment during search-and-rescue or combat operations. Similar technologies can be used to help the vision-impaired population as well.

APPENDIX A

PARTICIPANT INFORMATION

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Table 1. Details of the Participants

Subject	Subject Code	Gender	Age*
1	S01	M	21
2	S02	F	25
3	S03	F	30
4	S04	F	23
5	S05	F	20
6	S06	F	19
7	S07	M	25
8	S08	M	24
9	S09	M	21
10	S10	M	20

*Age on the date of the experiment

APPENDIX B

SUMMARY OF STATISTICAL ANALYSIS

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Table 2. Data Summary from SPSS ANOVA

(I) Condition	(J) Condition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Dependent Variable: SD_x						
NC	PC	1.7279*	.3204	.000*	.9642	2.4915
	VC	1.4842*	.3204	.000*	.7205	2.2478
PC	NC	-1.7279*	.3204	.000*	-2.4915	-.9642
	VC	-.2437	.3204	.728	-1.0073	.5200
VC	NC	-1.4842*	.3204	.000*	-2.2478	-.7205
	PC	. 2437	.3204	.728	-.5200	1.007
Dependent Variable: SDy						
NC	PC	1.7024*	.6176	.019*	.2307	3.1741
	VC	1.5387*	.6176	.038*	.0669	3.0104
PC	NC	-1.7024*	.6176	.019*	-3.1741	-.2307
	VC	-.1637	.6176	.962	-1.6354	1.308
VC	NC	-1.5387*	.6176	.038*	-3.0104	-.0669
	PC	.1637	.6176	.962	-1.3080	1.6354

Dependent Variable: SDvCoP$_x$						
NC	PC	16.0817*	1.5720	.000*	12.3353	19.8280
	VC	4.9324*	1.5720	.006*	1.1860	8.6787
PC	NC	-16.0817*	1.5720	.000*	-19.8280	-12.3353
	VC	-11.1493*	1.5720	.000*	-14.8956	-7.4029
VC	NC	-4.9324*	1.5720	.006*	-8.6787	-1.1860
	PC	11.1493*	1.5720	.000*	7.4029	14.8956
Dependent Variable: SDvCoP$_y$						
NC	PC	19.4847*	2.0475	.000*	14.6051	24.3642
	VC	9.2547*	2.0475	.000*	4.3752	14.1343
PC	NC	-19.4847*	2.0475	.000*	-24.3642	-14.6051
	VC	-10.2299*	2.0475	.000*	-15.1094	-5.3503
VC	NC	-9.2547*	2.0475	.000*	-14.1343	-4.3752
	PC	10.2299*	2.0475	.000*	5.3503	15.1094

(*) Implies significance.

APPENDIX C

MATLAB CODE FOR DATA ANALYSIS OF THE FORCE PLATE DATA

MATLAB CODE FOR DATA ANALYSIS OF THE FORCE PLATE DATA

```
clear all
A=xlsread(['Trial36.xlsx']);
P=20; % Overall data collection interval time Period (s) %
t=.0238; % thickness of force plate (m) %
Fs=1000; % Sample Frequency %
ti=(0:1/Fs:(P-(1/Fs)))'; % Time variable %
% Unassisted Attempt %
Fx=A(1:(P*Fs),1);
Fy=A(1:(P*Fs),2);
Fz=A(1:(P*Fs),3); % Retrieval of information from Excel %
Mx=A(1:(P*Fs),4);
My=A(1:(P*Fs),5);
COPx=(My+(Fx.*t))./Fz*1000; % Center of Pressure X (mm) %
COPy=(Mx-(Fy.*t))./Fz*1000; % Center of Pressure Y (mm) %
dCOPx=COPx-mean(COPx); % Position of COPx relative to the mean %
dCOPy=COPy-mean(COPy); % Position of COPy relative to the mean %
rCOP=sqrt((dCOPx.^2)+(dCOPy.^2)); % COP Deviation Magnitude %
dCOP=mean(rCOP); % Mean Deviation Magnitude (mm) %
MSAx=mean(abs(dCOPx)); % Mean Sway Amplitude Anterior-Posterior %
MSAy=mean(abs(dCOPy)); % Mean Sway Amplitude Medial-Lateral %
RMSx=rms(dCOPx); % Root Mean Square COPx position %
RMSy=rms(dCOPy); % Root Mean Square COPy position %
SDx=std(dCOPx); % Standard deviation of COPx %
```

```
SDy=std(dCOPy); % Standard deviation of COPy %
MD=max(rCOP); % Maximum Deviation Magnitude %
MDx=max(dCOPx); % Maximum Deviation Anteroposterior %
MDy=max(dCOPy); % Maximum Deviation Mediolateral %
y=fft(dCOPx)/(P*Fs); % Fast Fourier Transform of dCOPx %
y=abs(y); % Removal of imaginary or complex numbers %
y=2*y(1:1+((P*Fs)/2)); % Excluding mirrored results %
f_scale=Fs/2*linspace(0,1,P*Fs/2+1)'; % Scaling frequency input to sample frequency %
plot(f_scale,y),axis('tight'),grid('on'),title('Dominant Frequency')
xlim([0,2])
xlabel('Frequency (Hz)')
ylabel('COPx Spectral Density (mm)')
[pks,locs]=findpeaks(y,f_scale); % x and y locations of peaks in the plot %
if locs(1)<.06
   pk_dom=pks(2:end); % Excluding the zero frequency peak %
   [v,k]=max(pk_dom); % Retrieve the index for the tallest peak %
   if locs(k+1)==.05
      f_dom=locs(k+2) % Associate that index with locs to find the dominant frequency %
   else
      f_dom=locs(k+1) % Since the index k is for the max pk_dom, which skips the first object of pks, the index for locs must be k+1 %
   end
else
   [v,k]=max(pks);
```

```
f_dom=locs(k)
end
%%% Velocity of COP for both conditions:
fCOPx=movmean(dCOPx,Fs*.1); % Filtered COPx %
fCOPy=movmean(dCOPy,Fs*.1); % Filtered COPy %
%fCOPx2=sgolayfilt(dCOPx2,3,51); % Filtered COPx2 %
%fCOPy2=sgolayfilt(dCOPy2,3,51); % Filtered COPy2 %
vCOPx=diff(fCOPx)*Fs;
vCOPy=diff(fCOPy)*Fs;
vCOP=sqrt(vCOPx.^2+vCOPy.^2);
SDvCOP=std(vCOP);
SDvCOPx=std(vCOPx);
SDvCOPy=std(vCOPy);
%%% Plotting and Data Export %%%
plot(fCOPx,fCOPy)
title('COP')
xlabel('COPx (mm)')
ylabel('COPy (mm)')
%plot(ti,rCOP,'k.--')
%hold on
%plot(ti,rCOP2,'rs--')
%title('rCOP Assisted vs Unassisted')
%xlabel('Time (s)')
%ylabel('rCOP (m)')
%legend('Unassisted','Assisted')
```

```
%hold off

load=[dCOP,MSAx,MSAy,RMSx,RMSy,SDx,SDy,MD,MDx,MDy,mean(abs(
vCOP)),mean(abs(vCOPx)),mean(abs(vCOPy)),f_dom,SDvCOPx,SDvCOPy]
% Defines the Data Exported %

filename='Data Analysis - 15Nov.xlsx';

xlswrite(filename,load,3,'C15:R15');
```

APPENDIX D

ARDUINO CODE FOR GLOVE OPERATION

ARDUINO CODE FOR GLOVE OPERATION

```
uint16_t fingers_val = 0;

uint8_t i = 0;

uint8_t finger_sensors[3] = {A2, A1, A0};

uint16_t sensor_vals[3] = {0};

uint8_t vibe_pins[4] = {5, 9, 3, 6};

unsigned long on_start = 0;

unsigned long on_time = 0;

#define trigPin1 10  // was originally 8

#define echoPin1 11  // was originally 9

#define trigPin2 12  // was originally 10

#define echoPin2 13  // was originally 11

long duration;

float distance, UltraSensor1, UltraSensor2, AVGdistance;

char data;

String SerialData="";

float pastDistance = 0;

int MeasurementsToAverage = 2;

void setup()
{
 Serial.begin(9600);
```

```
  for(uint8_t i = 0; i < 4; i++)
  {
    pinMode(vibe_pins[i], OUTPUT);
  }

//  pinMode(trigPin1, OUTPUT);
//  pinMode(echoPin1, INPUT);
  pinMode(trigPin2, OUTPUT);
  pinMode(echoPin2, INPUT);


}

void loop()
{
  fingers_val = analogRead(finger_sensors[0]) + analogRead(finger_sensors[1]) +
analogRead(finger_sensors[2]);

  if(fingers_val < 350)
  {
    UltraSensor2 = SonarSensor(trigPin2, echoPin2);
    distance = UltraSensor2;

    if(distance < 2)
    {
      distance = pastDistance;
      AVGdistance = pastDistance;
    }
    else
    {
      AVGdistance = (999*pastDistance + distance)/1000;
      pastDistance = distance;
    }
    Serial.print("Distance measured by the Ultrasonic sensor: "
```

```
        Serial.print(AVGdistance);
        Serial.println(" cm");

    if (AVGdistance < cane_length && AVGdistance > (cane_length-3))
    {
      for(i = 0; i < 4; i++)
      analogWrite(vibe_pins[i], 0);
    }
    else
    {
      for(i = 0; i < 4; i++)
      analogWrite(vibe_pins[i], 55);
    }
  }
  else
  {
    for(i = 0; i < 4; i++)
    analogWrite(vibe_pins[i], 0);
  }
  return;
}

float SonarSensor(int trigPinSensor,int echoPinSensor)
{
  digitalWrite(trigPinSensor, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPinSensor, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPinSensor, LOW);
  duration = pulseIn(echoPinSensor, HIGH);
  return (duration/2) / 29.1;
}
```

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VITA

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