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Investigation of the information provided by light touch for balance improvement in humans

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INVESTIGATION OF THE INFROMATION PROVIDED BY LIGHT TOUCH FOR BALANCE IMPROVEMENT IN HUMANS

by

ANIRUDH SAINI

A THESIS

Presented to the Faculty of the Graduate School of the

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Approved by

Yun S. Song, Advisor
Ming C. Leu
Devin Burns

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ABSTRACT

This study investigates the information provided by Light Touch (LT) in improving human postural stability without mechanical assistance. Light Touch, an interaction force with a magnitude about 1 N, is known to improve postural stability in humans during quiet standing. However, the nature of the information from LT that helped improve balance is yet unknown. In this work, we hypothesized that LT provides information about one's body kinematics. We used a haptic robot to provide modulated, measurable light interaction force on the high back haptic location of humans to provide body kinematics-dependent information through LT. Standing balance experiments were performed with different force conditions on a group of ten healthy young participants. Results from these experiments have shown significant improvement in standing balance in conditions that provided LT over the condition that had no touch/contact. No further improvement was observed with additional position information provided in the form of variable vibration. Further data analysis revealed that the embedded information in LT provided in this study was partly position-dependent and mostly velocity-dependent. This positive effect of LT on back advances the research on implementing LT into wearable devices that can help improve postural stability of humans.

ACKNOWLEDGMENTS

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PAPER I

1. INTRODUCTION

There is a growing need for balance assistance in humans, especially in older population with higher risk of falls. Each year in the US, 2.8 million older adults are treated in emergency departments for injuries from falls, and over 800,000 patients are hospitalized due to fall injury such as head injury or hip fracture [1]. Falls are the most common cause of hip fracture (over 95% [2]) as well as traumatic brain injuries [3]. In 2015, the total medical cost to treat fall injuries was $50 billion, of which 75% were shouldered by Medicare and Medicaid [4]. Many people who fall, even if they are not injured, become fearful of falling and may result in reduced everyday physical activities. The reduced activity results in weaker physical composure which further increases their risk of falling [5].

Of many conditions contributing to falls, “difficulty with walking and balance” is identified as one of the most common factors [6]. For controlling the standing balance, the central nervous system uses sensory information from a wide range of sensory inputs, such as from the vestibular, visual, and somatosensory systems. It becomes difficult for an individual to control posture when there is a sensory information deficit.

Compensating the lack of adequate sensory information, Light Touch (LT), at the fingertip, was first used to improve postural stability during quiet standing in healthy adults [7]. Light touch is an interaction force with a magnitude of about 1 N or less, which was shown to improve balance in a wide range of population which includes healthy young adults [8], healthy older adults [9, 10], stroke patients [11, 12], individuals with Parkinson’s disease [13, 14], individuals with vestibular impairments [15], young individuals with muscle fatigue [16], peripheral neuropathy patients [17], people with congenital blindness [18], individuals with anterior cruciate ligament (ACL) injury, and individuals with multiple sclerosis [19]. Due to the effectiveness of LT in improving balance as well as its simplicity in its application, LT is considered a potential balance aid technique and a potential rehabilitation tool for balance [20].

Unlike most other works on LT in which LT is commonly applied at the fingertip, Johannsen used the interaction force applied at various haptic locations on the backside of the patients with stroke or Parkinson's disease [21]. Notably, LT was applied externally by a therapist trained with contact force feedback to maintain steady interaction – referred as Inter-Personal Touch (IPT). This work showed the potential to use externally applied LT, possibly for rehabilitation and assistive device design. However, it is unclear how LT from an external source (IPT) was able to improve human balance on patients with neurologic conditions. For example, the interaction force between the therapist and the patient cannot be strictly constant despite best efforts due to natural sway of both humans. In reality, there must have been some modulation of the interaction force that could have helped the patients improve their balance. That is, the IPT may have provided some information and not mechanical support with its low magnitude of force [20, 22, 23]. It is speculated that LT provides additional sensory information of one's position in the space [7, 24, 25]. Experiments on populations with reduced sensory information about body kinematics that used LT support this speculation [9, 26].

Despite the remarkable balance improvement from LT and its potential to become a useful balance rehabilitation scheme, there have been no studies till date aimed at investigating the nature of information provided by LT – mainly due to the inability to modulate the interaction force to carry specific, isolated information. In order to study the effect of information provided through LT, the interaction force must be controlled externally by the experimenter, and not by the human benefiting from it. In this context, experiments performed on rigid touch surfaces [7, 13, 26] are inadequate due to the fact that the modulation of the interaction force is performed entirely by the human participant. In this experiment setting, information in LT cannot be decoupled from the active modulation of force by the participant. Interaction forces in studies with softer objects, such as a curtain [8] or a flexible filament [27], may embed information about the touch location in space. However, these studies did not measure or report the force-displacement relationship and hence are not suitable to study the information embedded in the interaction force.

To overcome these obstacles to investigate the information provided by the LT, this research was aimed at studying the information provided by LT using a haptic robot. Specifically, we hypothesized that light interaction force provided by the haptic robot in relation to the trunk sway improves standing balance. Unlike passive physical objects, haptic robots can use virtual objects to deliver specifically designed interaction forces in which various information can be embedded. That is, haptic robots are capable of providing measurable and modulated light interaction forces, making it an ideal tool for investigating the information provided by LT.

The haptic robot (Phantom Premium 1.5/HF by 3D Systems) was used to provide LT on the high back location of the participants [21]. A highly sensitive force sensor (Nano17 by ATI Industrial Automation) was assembled to the tip of the haptic robot's end effector to measure the interaction force. A force plate (Optima OPT400600HF by Advanced Material Technology Inc.) was used to measure the ground reaction forces to measure the balance of the participants while standing. Two balance metrics, Mean Sway Amplitude (MSA) and the center-of-pressure velocity (CoP velocity, or dCoP) were calculated from the force plate data.

Three different interaction conditions were devised depending on the type of information provided by the haptic robot. No Force (NF) is the idle quiet stance with no contact with the robot, Commanded Constant Force (CCF) is where the haptic robot is commanded to provide a constant force, and a Commanded Constant Force with position-dependent Vibration (CCF+V) where position information was provided through variable vibration at the point of contact in addition to CCF. The participants stood barefoot in quiet bipedal stance, eyes closed, on a force plate with the haptic robot’s end-effector deliberately touching a prescribed location on the participants’ high back region (in CCF or CCF+V conditions only).

Standing balance in anterior posterior direction was improved significantly in both CCF and CCF+V conditions compared to the NF condition ($p < 0.001$). There was no significant difference between the CCF and CCF+V condition despite the additional positional information in the CCF+V condition.

The following section present a conference article with more details on the methods, results and discussion. Then, additional analysis on the implication of the information in CCF and CCF+V conditions are further analyzed and discussed.

PAPER

I. VELOCITY-DEPENDENT LIGHT INTERACTION FORCE IMPROVES STANDING BALANCE

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ABSTRACT

Light touch has been shown to improve postural stability in a wide range of population, including patients with neurological disorders. This study investigates the mechanism behind light touch that improves standing balance in order to translate light touch into a balance assistive device in the long term. We used a haptic device's end effector to produce light interaction forces on participants' back with a commanded constant force and position dependent vibration as the participants stood quietly with eyes closed. Their center of pressure data showed a significant improvement in their postural stability from the velocity-dependent interaction force, but not from the position-dependent vibration. This work supports the widely accepted, but not explicitly tested, idea that light touch acts to provide additional sense on one's body kinematics.

1. INTRODUCTION

Light interaction force, or Light Touch (LT), on fingertips was shown to improve human postural balance during standing [1-3]. Touching a stationary object with a fingertip with small force under 1 N was effective in reducing the center-of-pressure (CoP) sway in a wide range of population including healthy young adults [4], healthy older adults [5], stroke patients [6, 7], peripheral neuropathy patients [8], Parkinson’s Disease patients [9], and in anterior cruciate ligament (ACL) injury patients [10].

Due to the simplicity in providing LT and its effectiveness in improving balance, LT has the potential to become a useful balance aid [2]. For example, Johannsen [3] showed that the light touch provided by another person, or interpersonal touch (IPT), improved standing balance in patients with stroke or Parkinson’s disease. Unlike most other work in LT where the interaction force is provided to the fingertip of the participant, IPT was applied at various locations at the back of the patients by a trained therapist. It is unclear from this work, however, how LT in the form of IPT was able to improve human balance. The interaction force between the two standing humans with non-zero sway (patient and the therapist) cannot be strictly constant, despite best effort. Some modulation of force (not measured in [3]) could have helped the patients with their balance.

In this regard, understanding the nature of information provided by LT is the critical step towards harnessing LT as a practical balance aid. However, it is still unclear what the nature of the additional sensory information from LT is, that enabled human balance improvement. LT cannot be providing mechanical support, because the reaction force from LT is too small [2, 11, 12]. Instead, it is speculated (but not explicitly tested) that LT provides additional sense of one’s position in space [1, 13, 14]. LT experiments on populations with reduced sensory information about body kinematics supports this speculation [5, 10].

To date, no studies aimed specifically at investigating what information LT provides, mainly due to the inability to modulate the interaction force to carry specific, isolated information. In this view, experiments on rigid touch surfaces [1, 9, 10] are inadequate, because the magnitude and direction of the interaction force is modulated entirely by the human participant. That is, the experimenters have no control over the interaction force and therefore the information provided by it. On the other hand, interaction forces on softer objects, such as a curtain [4] or a flexible filament [15], could carry information about the displacement of the touch location. However, these studies did not measure nor report force-displacement relationship and therefore could not study the information potentially embedded in the interaction force profile. A similar limitation is found in the IPT work in [3].

To investigate the information embedded in LT that results in the balance improvement, this work used a haptic robot to provide measurable and modulated light interaction forces that carry specifically prescribed information. Unlike passive physical objects, haptic robots can be programmed to deliver specifically designed interaction forces in which various information can be embedded. This work hypothesized that LT provides information about one’s body kinematics, such as the displacement of the trunk, for better balance. Different light interaction force conditions and their effect in standing balance are presented and discussed.

2. METHODS

2.1. PARTICIPANTS

Ten participants aged between 19 and 27 years, three women and seven men, participated voluntarily in the study. The individuals were healthy with no neuromuscular injuries or known disorders. Prior to the experiment, all participants gave written consents approved by the Missouri S&T Institutional Review Board (IRB).

2.2. APPARATUS

Figure 1 depicts a participant standing barefoot in bipedal free stance, eyes closed, on a force plate while a robotic end effector is deliberately touching a haptic location on the participant's high back on the spine-line [3]. The Phantom robotic end effector (Phantom Premium 1.5/HF, 3D Systems) was equipped with a force sensor (Nano17, ATI Industrial Automation) where it touches the participant, to monitor the varying force between the participant and the end effector. The force plate (Optima OPT400600HF, Advanced Material Technology Inc.) measured the ground reaction forces and moments, which were used to calculate the center-of-pressure (CoP) of the participant.

2.3. PROCEDURE

The participants were first made aware of the three experimental conditions, in all of which the participant is asked to stand as quietly as possible with their eyes closed:

- No Force (NF) – an idle quiet stance on the force plate without contact with the haptic device.

- Commanded Constant Force (CCF) – The haptic device was *commanded* to exert a constant force on the participant's high back. Because the force was modulated in open-loop in the presence of non-zero friction at the joints, the actual (measured) interaction force applied to the participant was not precisely constant.
- Commanded Constant Force with position-dependent Vibration (CCF+V) – In addition to the commanded constant force, the haptic device provided a vibration in the mediolateral direction, whose magnitude is proportional to the anterior and posterior position of the touch location (Figure 1).

The participants were made aware of the force but were not instructed to maintain a specific force level nor to pay attention to the magnitude. The participants wore a skin-tight vest for the experiment to maintain the light interactive force on their body surface with high sensitivity and avoid disturbances due to loose clothes. The participants were given enough time to get comfortable with their stance on the force plate and to sway as little as possible for the entire trial [1]. Each trial began when the participants felt stable enough and said 'ready' or 'go'.

Each participant underwent 12 trials of each condition with a total of 36 trials. These 36 trials were block randomized into 3 blocks of 12 trials with 4 trials of each condition to eliminate any possible bias. Each trial lasted 20 seconds. Five minutes of mandatory breaks were taken between blocks.

A separate verification experiment was performed to identify the effect of friction in the CCF condition. As constant force was commanded, the end effector was pushed manually by the hand of the experimenter. The interaction force and the position information of the end effector from the haptic device were obtained and compared.

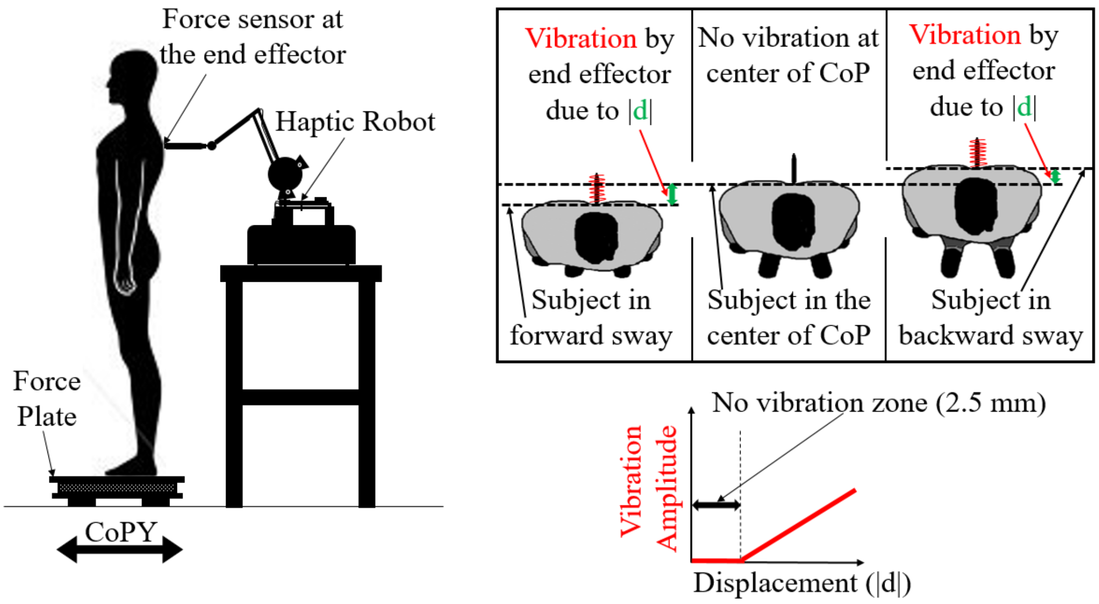

Figure 1. (Left) Schematic of a participant standing on the force plate and the haptic device end effector touching the high back location. (Right) Illustration of the position-dependent vibration in the CCF+V condition.

2.4. ANALYSIS

To eliminate possible learning effect, data from blocks 1 and 2 were not analyzed. The 12 trials from block 3 of each participant were processed using MATLAB (MathWorks) to obtain the CoP data, from which Mean Sway Amplitude (MSA) [15] and the anterior-posterior standard deviation of CoP (dCoP) [16] were obtained.

The CoP, and its characteristics, are calculated as

$$CoPX = -(M_y + F_x * t)/F_z; \quad CoPY = (M_x + F_y * t)/\mathrm{F_z} \qquad (1)$$

where *CoPX* and *CoPY* are CoP values in X and Y axes respectively, and *t* is the thickness of the force plate used. Standard deviation of CoP in anterior posterior direction (dCoP) is derived from the $CoPY$ direction. MSA was calculated using the following formula [15]:

$$MSA = \frac{1}{N}\sum_{i=1}^{N}|CoPY_i - \overline{CoPY}| \tag{2}$$

where,

$$\overline{CoPY} = \frac{1}{N}\sum_{i=1}^{N}CoPY_i \tag{3}$$

where N is the number of samples. Statistical analyses of MSA and dCoP across conditions were performed with ANOVA using SPSS (IBM).

3. RESULTS

The mean values and the standard errors of dCoP as well as MSA are shown in Table. 1. The values are comparable to other studies using these metrics [3, 15].

Table 1. Mean and standard error.

Condition	**dCoP (m/s)**		**MSA (m)**	
	Mean	***Std. Error***	***Mean***	***Std. Error***
CCF	0.024	0.001	0.019	0.001
CCF+V	0.025	0.001	0.020	0.001
NF	0.031	0.001	0.025	0.001

The interaction force during the CCF or the CCF+V conditions were between 0.4 N and 1.4 N with an average of 0.9 N, which is comparable to most LT force magnitudes in the literature [1, 15]. The variation is presumably due to the low, yet non-zero, friction in the joints of the haptic robot, exerting higher force on the participant as he/she leaned backwards, and lower force when he/she leaned forward. Indeed, a separate pilot experiment revealed that the interaction forces in the CCF and the CCF+V conditions were velocity-dependent (Figure 2).

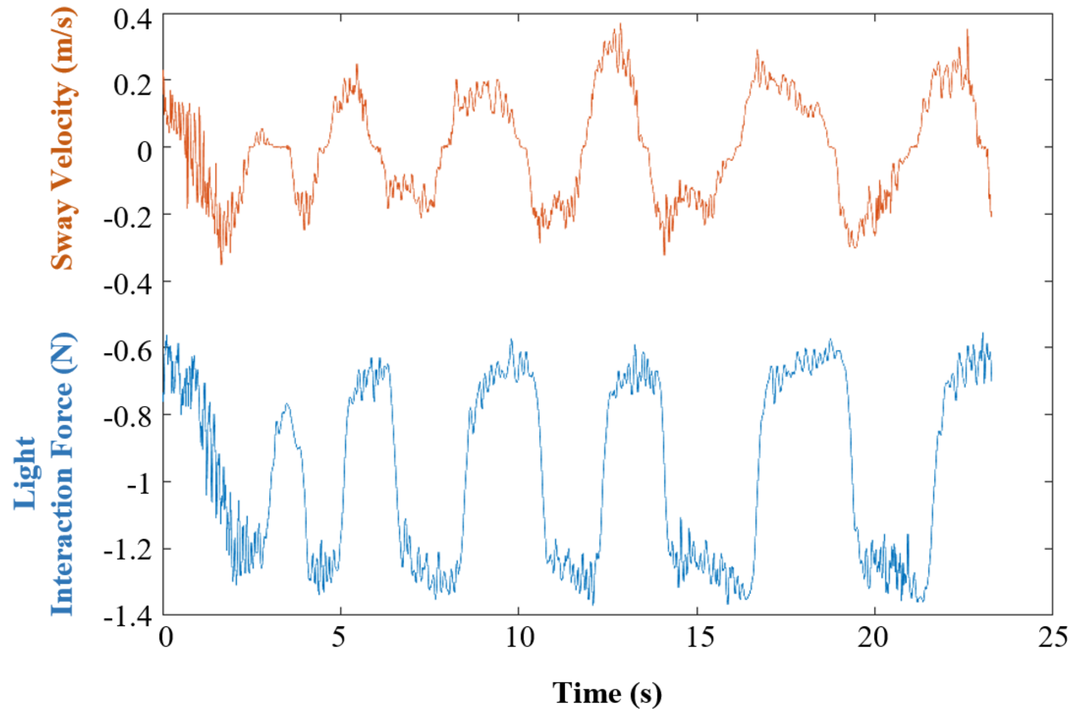

Figure 2. Relationship between the velocity of touch position (orange) and light interaction force (blue) shown in the time series. The velocity magnitudes are multiplied by ten for better illustration purposes.

Standing balance was improved due to the light interaction force applied by the haptic robot. Significant reductions in both MSA (Figure 3) and dCoP (Figure 4) were found from the NF to CCF ($p < 0.001$; Cohen's d for MSA is 0.8, and for dCoP is 0.7) as well as from NF to CCF+V ($p < 0.001$; Cohen's d for MSA is 0.7, and for dCoP is 0.6). The NF condition had the highest dCoP along with the highest MSA.

The added information about the trunk sway, presented as the position-dependent vibration in the CCF+V condition, did not further improve balance from the CCF condition. Both MSA and dCoP did not reduce from CCF to CCF+V condition ($p > 0.5$ and $p > 0.5$, respectively, Figures 3 and 4).

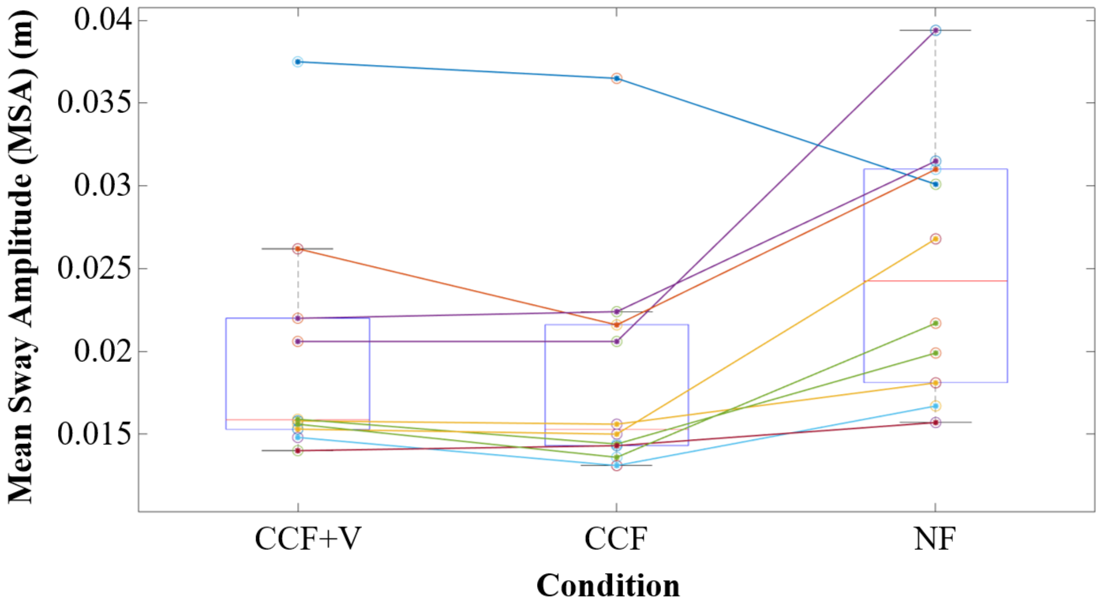

Figure 3. Mean sway amplitude of participants in anterior posterior direction (MSA) in three different conditions. Each line represents each individual participant's postural behavior.

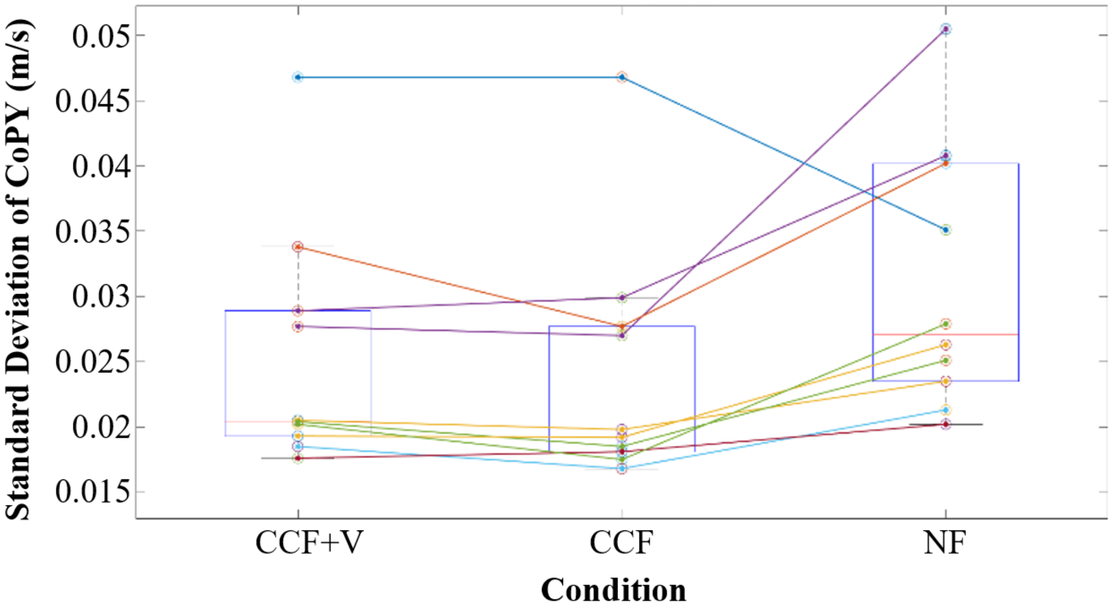

Figure 4. Standard deviation of center-of-pressure in anterior posterior direction (dCoP) in three different conditions. Each line represents each individual participant's postural behavior.

4. DISCUSSION

In this study, the participants had their eyes closed to increase the difficulty of quiet standing in healthy young population [1, 11, 13, 17, 18] by blocking visual information, and thereby simulating the population with balance difficulties. Tandem stance, another widely used means to increase the difficulty of standing in the mediolateral direction [1], was not used in this study because our LT aimed at providing information about one's anterior-posterior body kinematics.

The balance improvement from the CCF condition may be due to the sway direction information inferable from the interaction force (Figure 2). When the participant sways forward (positive velocity), the end effector also moves forward to maintain the contact with the participant. In the process, the haptic robot has to work against the static friction. As a result, the actual force applied to the participant is smaller than the commanded force until the sway velocity becomes zero. On the other hand, when the participant sways backward (negative velocity), the participant pushes against the commanded force as well as the static friction. As a result, the actual force applied to the participant is larger than the commanded force until the sway velocity becomes zero. In essence, static friction turned CCF condition provided velocity-dependent interaction force to the participants.

It should be noted that static friction is not deterministically repeatable, as represented by the irregularities in Figure 2. As a result, the velocity dependence of the interaction force is also not consistent. Despite this irregularity, the velocity dependence that produced roughly ±0.4 N modulation of force was sufficient for the participants to significantly improve their standing balance. This implies that the human body is able to take advantage of the information provided by subtle (< 0.4 N) changes in the force input for balance modulation.

In the presented experiment, the goal of our participants was to remain as quiet and stable as possible. That is, the participants were not instructed to pay attention to the interaction force. This was similar to the instruction given to the participants in [4] touching the curtain with his/her fingertip. In [4], this specific instruction resulted in no improvement of standing balance, suggesting that the improvement in balance from LT is a result of an additional supra-postural task implied by the experiment task – one which requires the participant to maintain a specific level of force against a specific position in space. However, unlike the supra-postural task in [4], participants in this study did not have to put extra effort to maintain the contact, maintain the force level, nor to remain in a specific location in space. Nonetheless, the CCF as well as the CCF+V condition resulted in reduced MSA and dCoP. This suggests that the improvement in balance from LT cannot solely be from the additional supra-postural task, and that the brain utilizes the extra information provided by LT for postural stabilization.

None of the individual participants showed a significant difference in MSA nor in dCoP between the CCF and CCF+V conditions, where the position dependent mediolateral vibration (Figure 1) was the only additional input in the CCF+V from the CCF condition. This implies that the additional position dependence was not necessary. One possibility is that the information provided by the direction-dependent force in the CCF condition was useful enough – that the extra information from the vibration was simply ignored. Another possibility is that the vibration did not provide sufficiently useful information, since it did not distinguish forward versus backward displacement. This may have confused the participants, not being able to use the information provided by the vibration. As an alternative, the vibration direction could have been different for the forward and the backward sway displacement. For example, vertical vibration could be applied in response to the forward displacement, whereas a mediolateral vibration could be applied in response to the backward displacement. However, the efficacy of such differentiated vibration would depend on the participant’s ability to distinguish vertical versus mediolateral vibration at the touch location.

Despite the limitations encountered in the experiment, such as the presence of static friction, externally modulated light interaction force provided by a haptic robot has been shown to help participants improve their postural stability. Motivated by this work, the team is currently working on a wearable balance assistive device with modulated haptic inputs. Such device could utilize more than one touch location at the back [3], or even include multiple touch locations on other parts of the body. Such device will initially assist standing balance and may broaden its application to other activities such as balance during walking.

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SECTION

2. FURTHER RESULTS AND ANALYSIS

A separate pilot experiment was conducted to study the relationship between the interaction force and the kinematics of the touch position in the CCF condition. This separate study was focused on developing a better understanding of the relationship between the trends of force modulation and sway direction, as observed during the human experiments especially in CCF condition. Due to friction at the robot joints and to the lack of force feedback, interaction force in the CCF condition was not strictly constant.

In this pilot experiment, the experimenter imitated the behavior of the body sway of a typical participant pushing the robot by his hand as shown in Figure 2.1. The interaction force between the robot and the hand was measured directly by the force sensor, whereas the robot joints measured the position of the touch location. The velocity and acceleration of the interaction point are calculated from the position data. At the beginning of this experiment, the experimenter abruptly pushed the tip of the end effector to generate a spike, in both the measured tip position as well as the interaction force data. Using the spike as a reference, the start and end timestamps of the collected data were matched together. To match the sampling rate of the position and force data, and thus the length of the dataset, the Spline function was used for cubic spline interpolation in MATLAB to resample both the data sets, for further correlation analysis. Then, the aligned and resampled data was analyzed to study the relationship between the interaction force and position, interaction force and velocity, and interaction force and acceleration to study which kinematic information CCF condition carried.

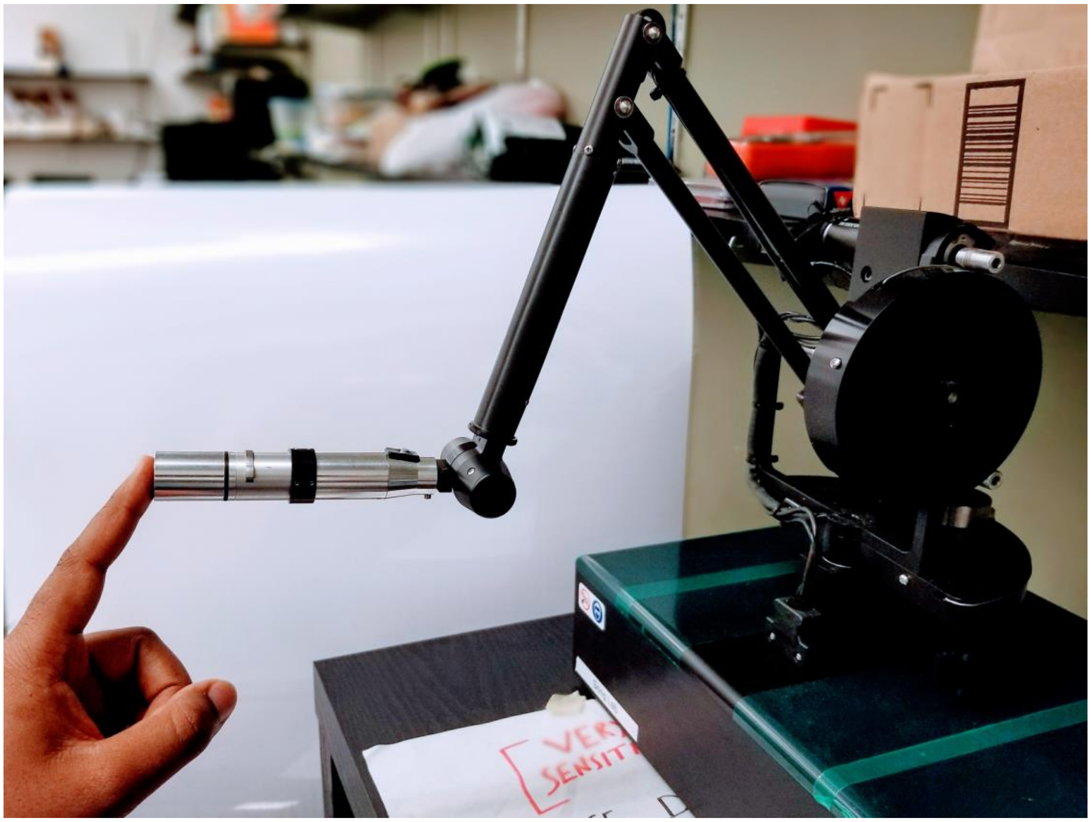

Figure 2.1. Separate pilot experiment with hand.

2.1. POSITION, VELOCITY, AND FORCE OVER TIME

The Light Interaction Force and Position are plotted against time as shown in Figure 2.2, where the force magnitude is amplified by eight times for better illustration.

Some correlation can be observed between the sway direction from the position data and the change in interaction force.

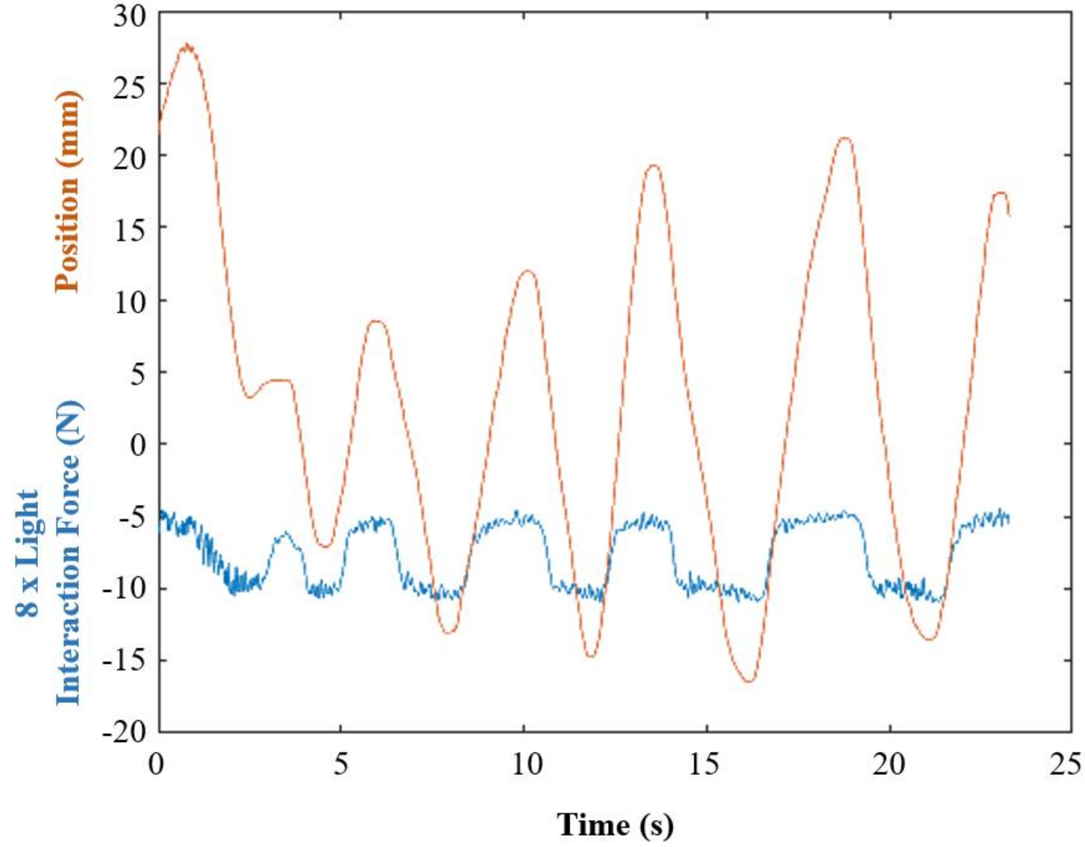

Figure 2.2. Relationship between the tip position (orange) and light interaction force (blue) shown in time series.

The Light Interaction Force and Velocity are plotted against time, as shown in Figure 2.3, where the velocity magnitude is amplified by ten times for better illustration. From this graph, the relationship between velocity and interaction force is found strong.

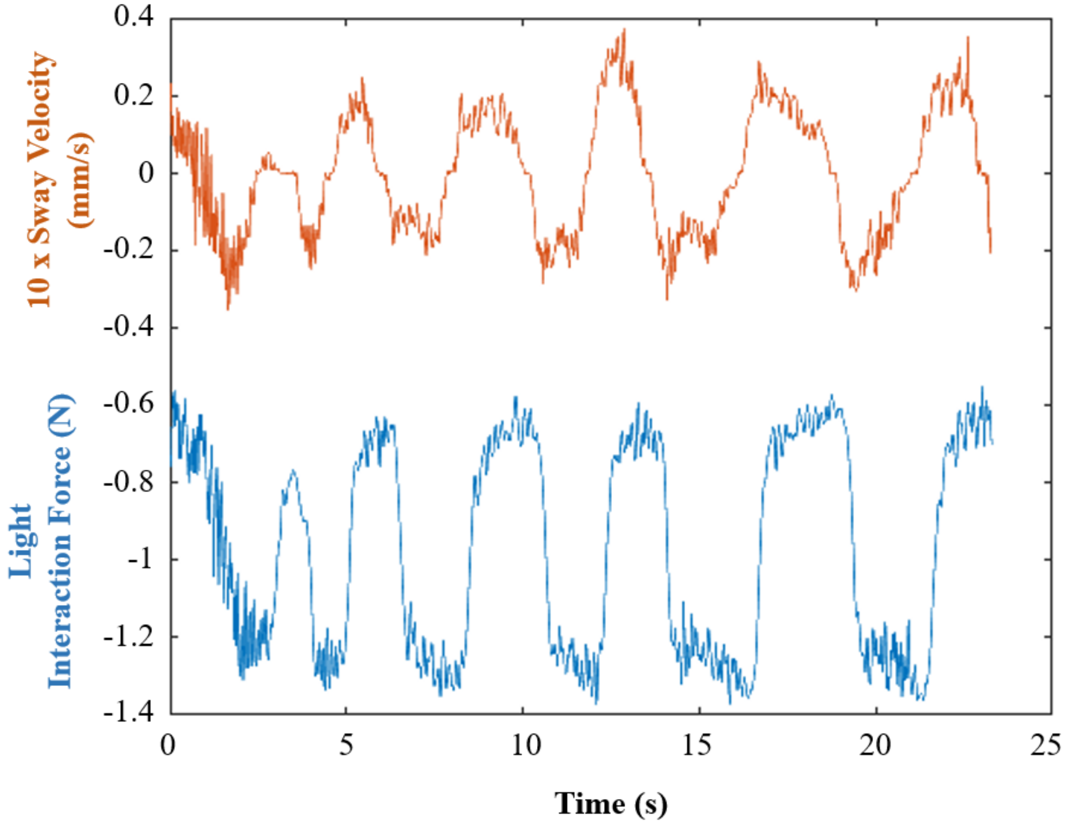

Figure 2.3. Relationship between the velocity of tip position (orange) and light interaction force (blue) shown in time series.

2.2. CORRELATION BETWEEN THE INTERACTION FORCE AND TOUCH POSITION KINEMATICS

To study what kinematic information is carried in the CCF condition, the interaction force was correlated against the position, velocity, and acceleration of the touch location.

2.2.1 Correlation between Force and Position. The correlation between the light interaction force and position is shown in Figure 2.4, with $R^2 = 0.51$. This correlation between force and position implies some correlation between them.

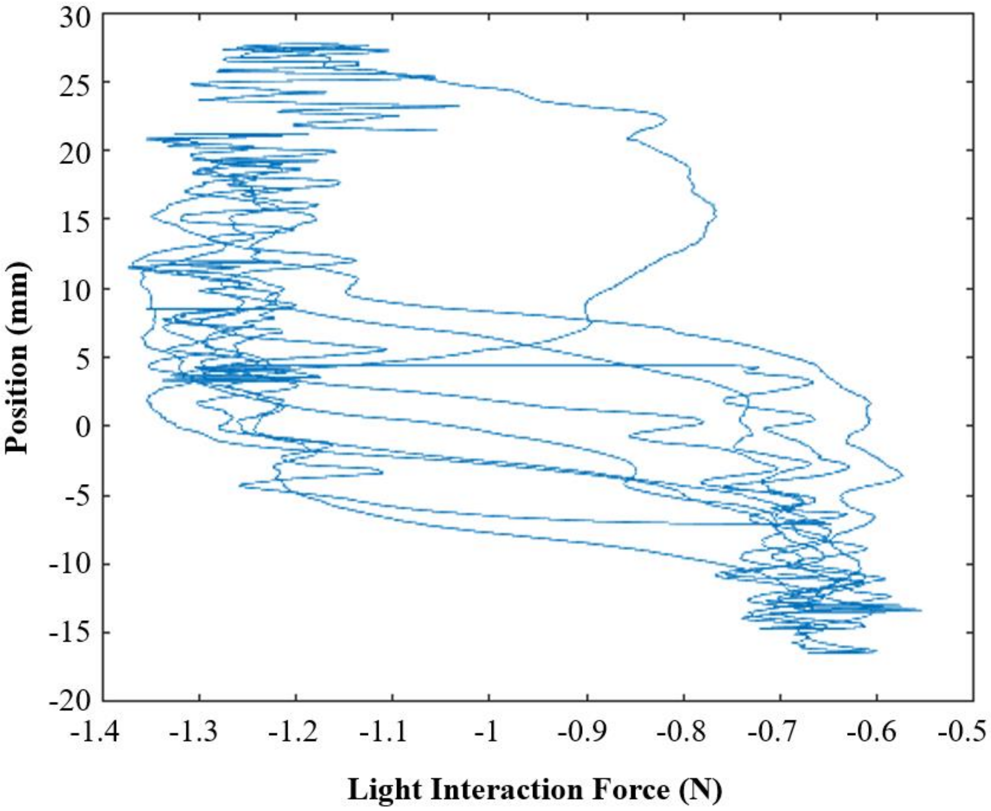

Figure 2.4. Relationship between light interaction force and position.

2.2.2 Correlation between Force and Velocity. The correlation between light interaction force and sway velocity is shown in Figure 2.5, with $R^2 = 0.79$. This implies high correlation between the force and velocity. The horizontal lines in the middle of the plane can be the effect of static friction of the haptic device.

2.2.3 Correlation between Force and Acceleration. The correlation graph of light interaction force against sway acceleration is shown in Figure 2.6, with $R^2 = 0.02$. This implies hardly any correlation between the force and acceleration.

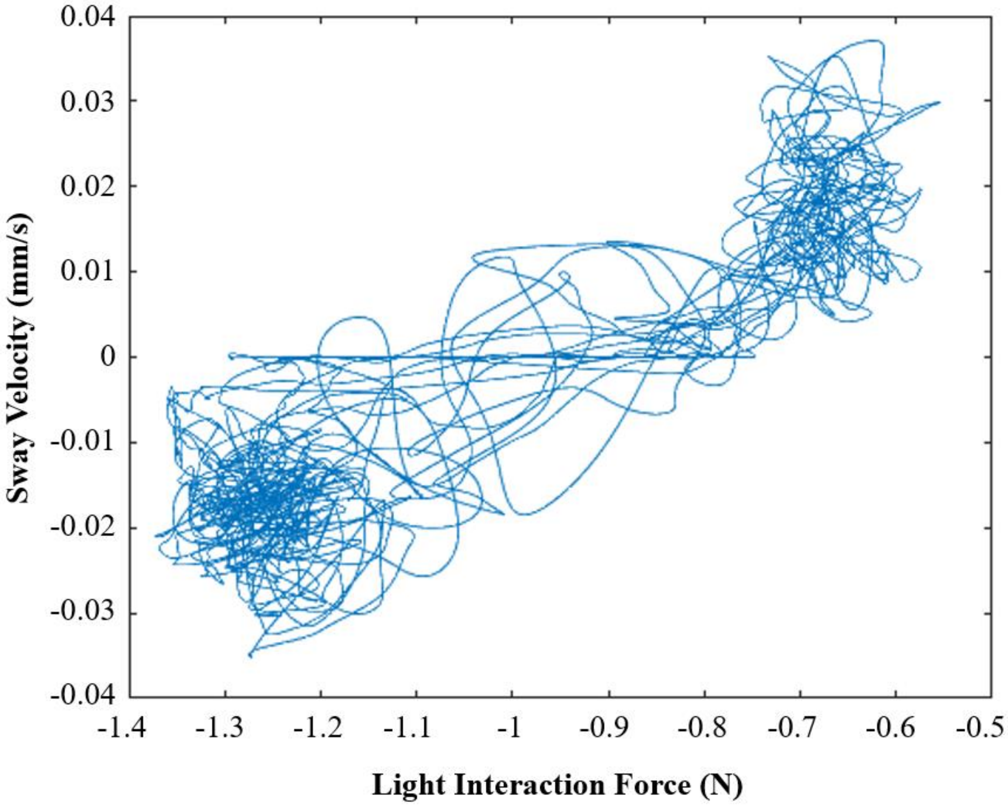

Figure 2.5. Relationship between light interaction force and sway velocity.

The velocity-dependence of the interaction force may be due to the static/kinetic friction of the joints in the haptic robot, as well as the time delay in the force generation loop of the robot. When the participant's sway occurs forward (away from the robot), the interaction force will be lighter because the force generated by the robot must overcome the static/kinetic friction. On the other hand, if the participant's sway occurs backward (towards the robot), the interaction force will be stronger because the backward motion is against both the static/kinetic friction and the force generated by the robot. Furthermore, the time delay in the process of maintaining a constant force by the robot through following the participant's sway adds to the velocity dependence of the interaction force. The moderate dependency of force to position may be due to the fact that the applied motion is sinusoidal – i.e., because the position profile and the velocity profile is not independent of each other.

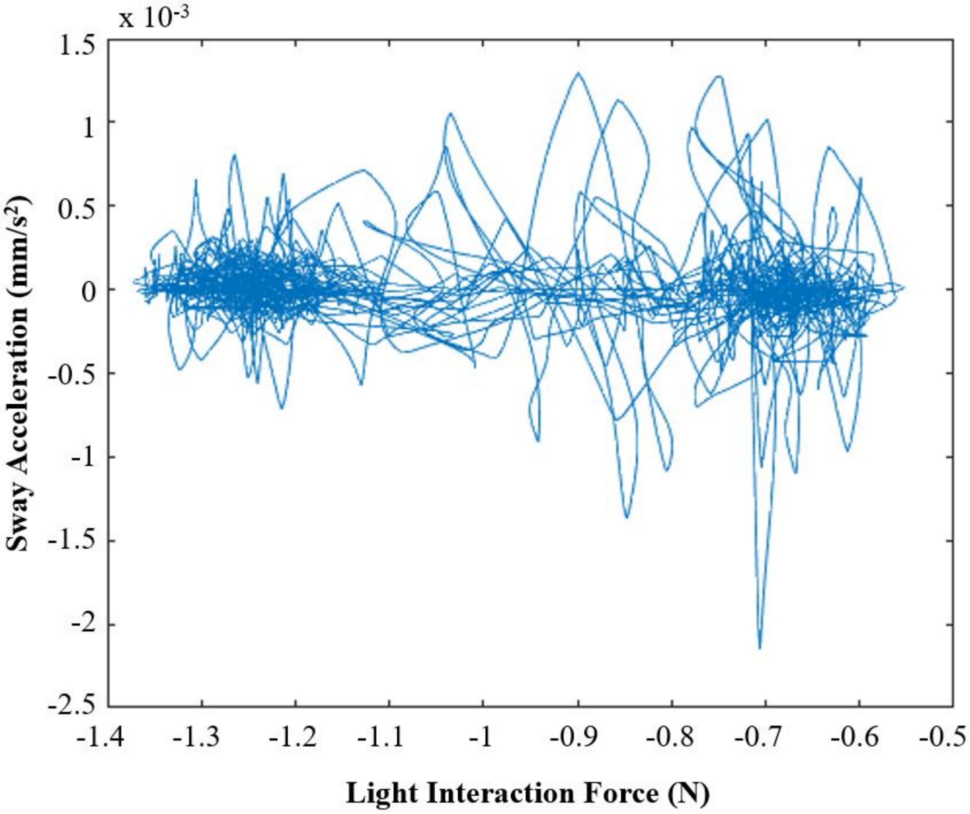

Figure 2.6. Relationship between interaction force and sway acceleration.

3. CONCLUSION

In this research, we used a haptic robot to investigate the information embedded in light touch (LT) that improves standing balance in healthy young adults. By investigating the information carried in the commanded constant force (CCF) condition, it is revealed that the information carried is mostly velocity related and slightly position related. No improvement was noticed in the commanded constant force with position dependent vibration (CCF+V) condition compared to that of CCF condition despite the additional positional information provided, suggesting that velocity-dependence is the key information that the participant benefit the most from.

With the light interactive touch provided by a robot (not by a human), promising results were found with significant balance improvement. This concept can be replicated into a wearable balance assistive device to improve standing balance. In this regard, the immediate future work includes developing a balance assistive wearable device that carries the trunk velocity information to the user and to verify its efficacy through human experiments.

APPENDIX A

PARTICIPANT INFORMATION

Table 1. Details of the Participants.

Subject	Subject Code	Gender	Age*	Comments from the participant/experimenter
1	S01	M	20	Bent knees during trials to minimal sway
2	S02	M	21	Inconsistent hand posture during trials
3	S03	F	19	N/A
4	S04	M	24	N/A
5	S05	M	20	N/A
6	S06	M	26	No-Force condition is most comfortable
7	S07	F	19	N/A
8	S08	M	23	N/A
9	S09	F	21	Very relaxing and refreshing
10	S10	M	24	Very comfortable to do

*Age on the date of the experiment

APPENDIX B

SUMMARY OF STATISTICAL ANALYSIS

Table 2. Collective Data Summary from SPSS ANOVA.

(J) Condition	(J) Condition	Mean Difference (I-J)	Std. Error	Significance	95% Confidence Interval	
					Lower Bound	Upper Bound
Standard Deviation in Anterior Posterior Direction (dCOP)						
CCF	NF	-0.0070*	0.00116	0.000*	-0.0097	-0.0042
	CCF+V	-0.0013	0.00116	0.511	-0.0040	0.0015
NF	CCF	0.0070	0.00116	0.000*	0.0042	0.0097
	CCF+V	0.0057*	0.00116	0.000*	0.0029	0.0084
CCF+V	CCF	0.0013	0.00116	0.511	-0.0015	0.0040
	NF	-0.0057*	0.00116	0.000*	-0.0084	-0.0029
Mean Sway Amplitude (MSA)						
CCF	NF	-0.0064*	0.00090	0.000*	-0.0085	-0.0042
	CCF+V	-0.0010	0.00090	0.482	-0.0032	0.0011
NF	CCF	0.0064*	0.00090	0.000*	0.0042	0.0085
	CCF+V	0.0053*	0.00090	0.000*	0.0032	0.0075
CCF+V	CCF	0.0010	0.00090	0.482	-0.0011	0.0032
	NF	-0.0053*	0.00090	0.000*	-0.0075	-0.0032

(*) Implies significance.

APPENDIX C

SEQUENTIAL INSTRUCTIONS FOR THE EXPERIMENTER

- **Prior to participant's arrival**
    - Turn on and setup AMTI Force Plate and Phantom Motors
    - Fix the ATI Force Sensor onto the Phantom Arm carefully, make sure the cable won’t touch the participant.
    - Setup the Visual Studio, AMTI NetForce and ATI software
- **As soon as the participant enters the lab**
    - Subject's consent form, Demonstration of the experiment and queries
    - Note the Y, Z coordinates of the haptic location with X as zero by modifying (enabling) lines 93 and 262 in the program code thereby using the Phantom with motors off only for this step. Mark a line by the front portion of their legs for reference.
    - Subject should change to their respective skintight vest.
    - Meanwhile, add the Y, Z coordinates to the code at lines 63 & 64 respectively and remodify (disable) the lines 93 and 262.
- **Start of the experiment**
    - Change the output file name series according to the subject code.
    - Click on start and then ask the subject to stand on the force plate behind the marked line.
    - Whenever they're ready, they say go or ready and immediately click on “arm” button in the AMTI window.
    - By the end of 20 seconds, the graphic window will be filled to the end, then click on stop, inform the participant that the trial ended, and then export the file. Repeat for every trial.

- **During and at the end of the experiment**
    - Make sure to save each trial with the corresponding subject code and trial number.
    - Observe the participants sway behavior and make notes if you find anything wrong or if they ask or say anything.
    - Monitor the force sensor readings on the ATI sensor frequently.
    - Give a mandatory break of at least 5 mins, to the participants, after every block of experiments.
    - Once again check all the saved data files and make sure there are 36 by the end of a participant's balance study.
    - Once done and the participant is gone, save and close all the software windows and secure the consent form and the datasheet with remarks and experimental information for future uses.
- **Understanding the three experimental conditions**

(i) Constant force with variable vibration at High back haptic location on the back. (CCF+V)

a. After the subject stabilizes with their stance on the force plate, the end effector's tip must be brought into contact with the subject's high back location, which lies on the back of spine line at about two inches lower to the shoulder line.

b. In the interface window, press 1 for CCF+V condition and to remove the condition, press any key other than 1 and 2 (Ideally, the space bar).

   c. The amplitude of vibration is related to the changing position of the end effector in the anterior and posterior direction.

(ii) Constant force at High back haptic location on the back. (CCF)

Similar steps, but with no vibration and just the constant force, press 2 for CCF condition.

(iii) No force/support (Free stance, NF)

Make the subjects stand a little ahead of their usual standing position so that the projected end effector doesn’t touch/disturb their stance.

[IMPORTANT NOTES: WHILE STOPPING THE FORCE, MAKE SURE THE PHANTOM IS HAND HELD, IF NOT IT HITS THE TABLE WITH ITS DROP, WHICH AFFECTS THE HAPTIC DEVICE.]

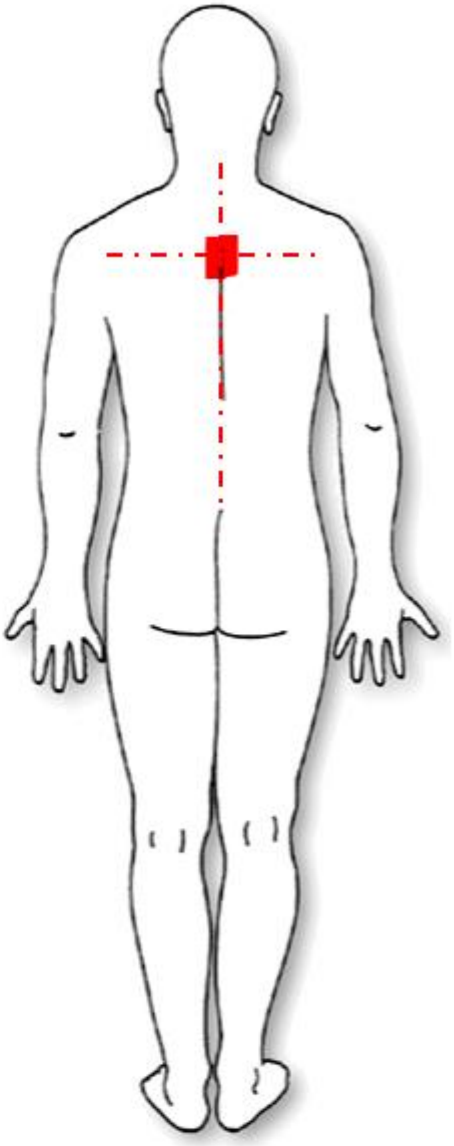

Figure C.1. Locating the high back haptic location [21].

APPENDIX D

VERBAL INSTRUCTIONS TO THE PARTICIPANTS

Describing the three conditions in the experiment:

a) No Force (NF): This will be the basic condition where you just stand on the force plate, barefoot and eyes closed, no contact or support from any object and all you have to do is to sway as little as you can since zero sway is impossible.

b) Commanded Constant Force (CCF): In this condition the robotic arm touches you on your back and pushes you with a very lightly and you follow the same instructions as before.

c) Commanded Constant Force with Vibration (CCF+V): In this condition, besides the light contact force, there is some vibration produced by the robotic arm whenever you sway beyond the no vibration zone of 5mm along your original COP in the anterior posterior direction. The more you sway in direction, the more amplitude the robotic arm vibrates with. Please don't panic if it vibrates frequently in this condition, it is totally okay and normal for anyone to sway like that.

Instructions for the Experiment (with Demonstration):

1. Stand barefoot on the force plate with your foot apart, approximately to your shoulder width, facing straight ahead, eyes closed with your back towards the robot, do not step on the 'X' marked on the force plate.
2. Take as much time as desired to maintain the stance as comfortably as possible for the entire trial, to sway as little as possible
3. Once felt ready for the trial, say "GO or READY" and from that moment data acquisition starts.
4. The trial ends in 20 seconds from the moment you say "GO or READY"

APPENDIX E

MATLAB CODE FOR DATA ANALYSIS OF THE FORCE PLATE DATA

```
A=xlsread('S05- (35).xlsx'); %Inputfilename.xlsx%

Fx=A(:,1); %Assigning names to arrays%
Fy=A(:,2);
Fz=A(:,3);
Mx=A(:,4);
My=A(:,5);
Mz=A(:,6);
T=linspace(5,20000,4000); %Declaring time array%
T=T'; %Time%
t=23.8; %thickness of the force plate%
X=-(My+(Fx.*t))./Fz; %COP in X-direction%
Y=(Mx-(Fy.*t))./Fz; %COP in Y-direction%

sY= size(Y);    %size of Y%
dY= zeros((sY(1)-1),sY(2)); %change of Y%
for i=1:(sY(1)-1)
    j=i+1;
    dY(i)=Y(j)-Y(i);
end

dT= zeros((sY(1)-1),sY(2)); %change of time%
i=1;
for j=2:sY(1)
    dT(j-1)=T(j)-T(i);
end

VY=(dY./dT); %velocity, first differential of Y%
sT= size(T);
dT= zeros((sT(1)-1),sT(2));
for  i=1:(sT(1)-1)
     j=i+1;
dT(i)=T(j)-T(i);
end

barY=(sum(Y))/(j);
MSA=(sum(abs(Y-barY)))/(j) %Mean Sway Amplitude%
load=[ range(X) range(Y) mean(X) mean(Y) std(X) std(Y)
min(dY)*100 max(dY)*100 std(dY) MSA];
filename = 'subjectcode#trial.xlsx'; %Outputfilename.xlsx
xlswrite(filename,load,5,'D1:M1');
%spreadsheet#,’DesignatedArea’%
```

APPENDIX F

EXCERPT FROM THE C++ PROGRAM FOR THE HAPTIC ROBOT OPERATION

The code can be found in the Visual Studio file FrictionlessSphere_VS2010.sln, which is located at C:\OpenHaptics\Developer\3.4.0\LTonBack in the PC labeled R04SONGYUN of MAE department at Missouri University of Science and Technology.

```
Logics used in the C++ code, to maintain forces and produce
variable vibration.

//Force on Back

float hy = 250;  //Fixed Height
float hz = 25;  //Fixed Depth  ** Works in Negative Z Ranges

float bx;    //Fixed Force in X Direction
float by;    //Fixed Force in Y Direction
float bz;    //Fixed Force in Z Direction

//Vibration
float v;     //Value Holder for Sinusoidal Function.
float i = 0; //Iteration Number, used to calculate sine
float g;     //Vibration Intensity Gradient

 //If statements exist to prevent extreme force application
and protect the robot.
 //Take care to alter these values incrementally.

 //Fix X Axis
 bx = -1 * (position[0]);

 if (bx > 1)
 {
   bx = 1;
 }
 if (bx < -1)
 {
   bx = -1;
 }

//Fix Y Axis
 by = 1 *(hy - (position[1]));

 if (by > 1.5)
 {
   by = 1.5;
 }
```

```
 if (by < -1.5)
 {
  by = -1.5;
 }

 //Fix Z Axis
 bz = 1 *(hz - (position[2]));

 if (bz > 1)
 {
  bz = 1;
 }
 if (bz < -1)
 {
  bz = -1;
 }
 if (r == 49)//Vibration
 {
  // Sine Function for Vibration
  i = i + .50;
  v = sin(i);
  g = abs(hz - (position[2]))  / 60;

  //Dead Zone:  No vibration less than 2.5mm or greater
than 2.5mm from set value hz
  if (position[2] < (2.5 + hz) && position[2] > (-2.5 +
hz))
  {
   g = 0;
  }

  bx = (1*g*v) + bx;   //Multiplies sine function by
gradient and adds whatever force is used to keep x axis
position fixed
  bz = 0.5;       //Constant z axis force
 }

 if (r == 50)//Constant Z Axis Force
 {
  bz = 0.5;
 }
```

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VITA

Anirudh Saini earned a Bachelor of Technology degree in Mechanical (Mechatronics) Engineering from Jawaharlal Nehru technological University Hyderabad, India in May 2016. Immediately after that, he joined the graduate school at Missouri S&T, worked initially as Graduate Teaching Assistant and later started research work as a Graduate Research Assistant under Dr. Yun Seong Song, from the Department of Mechanical and Aerospace Engineering. His thesis was in the field of Rehabilitation Robotics under the esteemed guidance of Dr. Song. He earned his Master of Science degree in Manufacturing Engineering from Missouri University of Science and Technology, Rolla in May 2018.

During his term at Missouri S&T, Mr. Saini became member of professional associations like IEEE, IISE, and always had keen interests in Advanced Manufacturing, Operations, and Continuous Improvement. He also achieved a Green Belt Certification in Six Sigma, by IISE.