Virtual Pebble: a Haptic State Display for Pedestrians

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Abstract— **We present a wearable haptic feedback device for the foot, which gives the sensation of a small pebble in a shoe when actuated and no sensation otherwise. Because it stimulates slowly-adapting as well as fast-adapting mechanoreceptors it is useful for displaying a condition that may persist over time, as well as the occurrence of an event. The feedback, which we call the "virtual pebble" due to its ability to appear on command, is intended as a complement to vibration feedback. We performed a user study to quantify perception accuracy during standing, walking, and jogging for haptic feedback combinations on the foot and knee from vibrotactors and the virtual pebble. We also quantified absolute perception thresholds for single vibration and virtual pebble actuations. Results show that subjects are able to correctly perceive a combination of the pebble and vibration much more accurately than a combination of two vibrations. In addition, subjects are most sensitive to vibration feedback while stationary but most sensitive to virtual pebble feedback while jogging. These findings suggest that the virtual pebble is useful as an additional channel of haptic feedback during ambulatory locomotion.**

I. INTRODUCTION

Haptic feedback has been shown to enhance learning during acquisition of new force and motion tasks [1], [2], and several studies have demonstrated the effective use of multiple vibrotactors for learning new motions [3], [4], [5], [6]. Vibrotactile feedback tends to work best when vibrotactors are spaced far apart and extraneous vibrations are minimized. Hence, it would be much easier to detect and distinguish two vibrating cell phones, one in each pocket, while sitting quietly at a desk as opposed to walking down a crowded sidewalk with both cell phones in the same pocket. Vibration detection difficulty also increases as the desired task becomes more involved or the speed of movement increases [7], [8].

Walking is an essential part of human existence and arguably the most important human movement. Gait retraining could assist those with neurological disorders, such as cerebral palsy and stroke, in regaining normal ambulation or be used as a preventative measure for musculoskeletal diseases such as osteoarthritis [9], [10]. Walking and jogging normally produce vibrations that stimulate fast-adapting type II mechanoreceptors, which can make it challenging to detect and distinguish the vibrations produced by wearable feedback devices. In addition, sustained vibration feedback can lead to desensitization [11], which makes vibration undesirable for displaying state information that persists over time.

Since it works well to place haptic feedback devices near the location of desired movement [12], recent studies have used vibration feedback on the foot to train changes in foot angle and foot pressure [3], [9]. Others have used foot vibrations for instant messaging communication and to simulate walking over different terrains [13], [14]. However, multiple simultaneous vibrations are rarely used on the foot during walking, likely due to difficulties in user perception.

In the following sections we introduce the virtual pebble design and then describe a perception experiment comparing it with vibration during jogging, walking, and standing.

II. VIRTUAL PEBBLE

The virtual pebble (Fig. 1A) is motivated by the idea that a person walking with a pebble in her shoe will be motivated to get rid of it. The feeling should not be painful, but a little annoying to convince the subject to change something. In the case of motion retraining, the virtual pebble could act as an indicator of a specific gait parameter or of overall performance. When motion needs to be corrected, the subject feels the pebble, otherwise it disappears.

The virtual pebble presents a protuberance in the insole of a shoe, which stimulates a combination of slowly-adapting (SA) and fast-adapting (FA) mechanoreceptors as the skin of a subject's foot presses against it. The actuation is non-backdrivable and consumes little power because it changes state while the subject's foot is in the air and forces are low. Most of the haptic sensation is produced by the subject's own footfall.

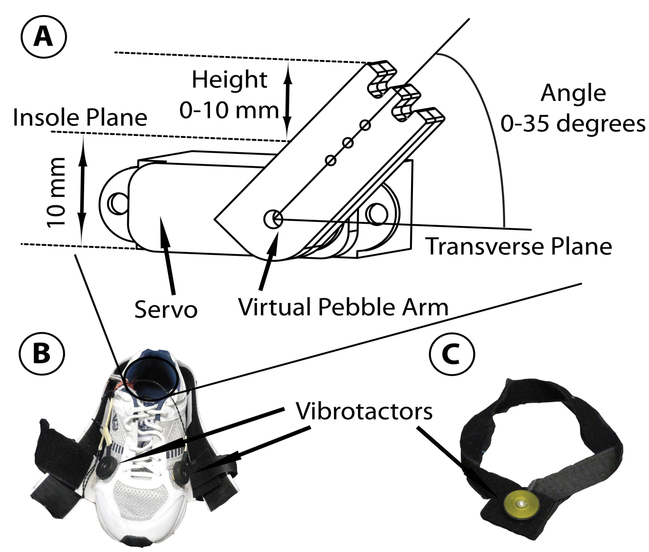

Fig. 1. The virtual pebble (A) consists of a small servo motor and a rotating arm (20.3×7.6×4.6 mm), embedded in the heel of the shoe (B). Two vibrotactors (C2 tactors) are attached to the outside of the shoe and one to the outside of the knee via Velcro straps (B), (C).

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Design choices include actuator placement, shape, and height. Several studies suggest that the heel of the foot is a good location to administer haptic feedback as it contains a cluster of mechanoreceptors with a relatively low threshold for detecting tactile stimuli [15], [16], [17]. In addition, it is located over the heel of the shoe, which provides room for an actuator.

We used a small servo gearmotor (Cirrus CS-5.4 with dimensions 20.0×8.0×17.6 mm) embedded in the heel of a running shoe (Fig. 1B). To determine actuator shape, we performed pilot studies testing several "pebbles" by having pilot subjects step on different shaped and sized plastic beads. We found that sharper edges on smaller beads allowed us to get the same perception as rounded edges on large beads. With this in mind, we designed and laser cut several plastic arm pieces, performed more pilot studies, and finally settled on a 20.3 ×7.6×4.6 mm shape (Fig. 1A) that was not painful to users wearing socks, but easily perceptible. The actuation height is adjusted for different users and conditions, and depends on skin and sock thickness, the subject's weight and whether the subject is stationary or active.

III. PERCEPTION TESTING

A user study was performed to evaluate user perception of the virtual pebble and vibrotactile stimulation while standing, walking, and jogging. Ten healthy subjects ages 21-30 voluntarily took part in this study, which was approved by Stanford University's Institutional Review Board. Seven participants were right-footed, and three left-footed. Half of the subjects had some prior experience with haptic feedback. The experiment consisted of two tests: Test 1 was meant to establish absolute perception thresholds for a single vibrotactor or the virtual pebble on the foot. Test 2 evaluated each subject's ability to identify various combinations of vibration and virtual pebble. Both tests were performed on a treadmill under three conditions: standing, walking (1.25 m/s), and jogging (2.05 m/s).

In addition to the virtual pebble, described in the previous section, we used three vibration motors (C2 Tactor by Engineering Acoustics, Inc.). One was placed on the medial side of the right foot near the head of the first metatarsal and another on the lateral side of right foot near the head of the fifth metatarsal (Fig. 2A). The third vibration motor was placed on the outside of the right knee near the lateral femural epicondyle (Fig. 2A). Vibrations were actuated at 250 Hz, near peak sensitivity of FA type II mechanoreceptors [18], [19], for a duration of 500 milliseconds at 100 milliseconds after heelstrike was detected for each gait cycle, based on previous findings regarding the best timing for vibration feedback in walking and jogging [20]. Velcro straps were used to ensure a proper fit and minimize the movement of vibrotactors during trials.

Haptic actuators were controlled through an Arduino Mega microcontroller board via serial connection (Fig. 2C). A force sensitive resistor (FlexiForce by Tekscan) was used on the heel to detect heel strike during each gait cycle. Symbols and abbreviations for haptic actuators are depicted in Fig. 3.

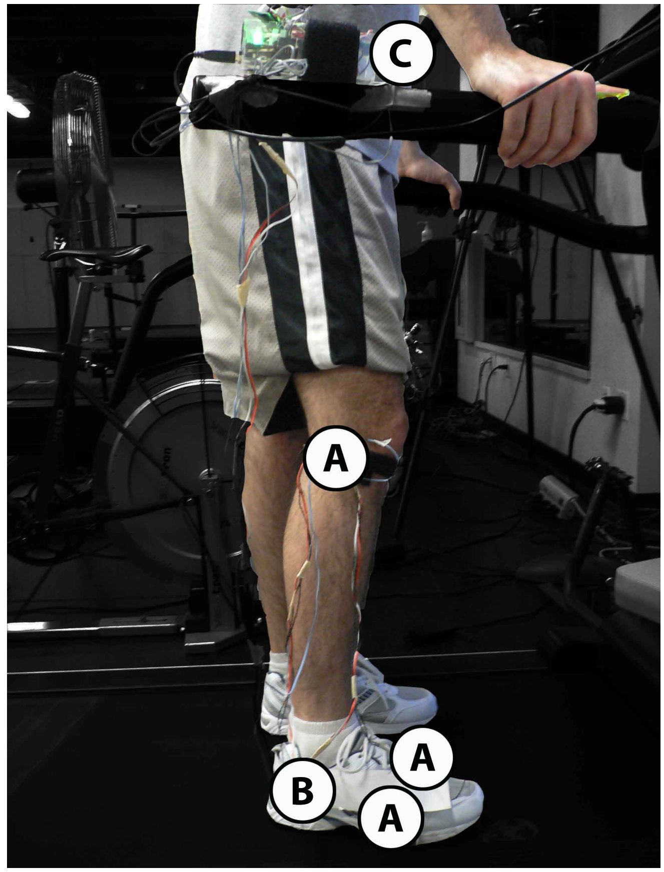


Fig. 2. Experimental setup showing a subject standing on the treadmill with three vibrotactors (A) attached to the knee and foot and one virtual pebble (B) underneath the heel. A microcontroller (C) receives heelstrike signals and controls the haptic actuations.

A. Test 1: Perception Thresholds

Subjects wore the customized running shoes with an embedded virtual pebble and three vibration motors, as previously described. Subjects also wore sound-blocking headphones to prevent detection of haptic actuations via audio cues.

We tested absolute perception thresholds for vibration on the medial side of foot (VL), and the virtual pebble underneath the heel (P) for standing, walking, and jogging. The order of conditions and types of feedback were randomized and counterbalanced across all subjects. We used a one-up

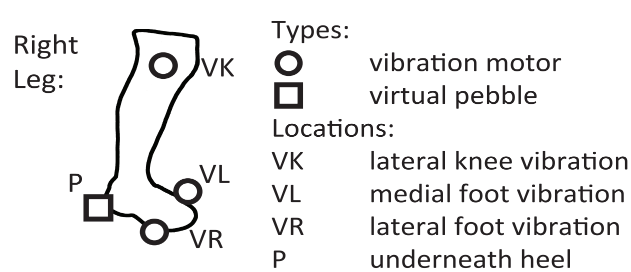


Fig. 3. Symbols and abbreviations for haptic feedback types and locations

three-down method [21] for estimating the threshold values by implementing a similar algorithm found in [22]. The initial amplitude for the vibration motor was peak-to-peak acceleration of 0.50 m/s^2, and the initial virtual pebble angle was 5 degrees, corresponding to a height of 1.7 mm (just below the insole plane in Fig. 1). The step sizes for vibration and virtual pebble were 0.10 m/s^2 and 5 degrees. If the subject did not feel the actuation, the actuation level was increased by the step size. If the subject felt the actuation three times in a row, the actuation level was decreased by the step size. A reversal was defined as a change in direction from increasing to decreasing actuation level or vice versa. After five reversals, the step size was decreased to 0.02 m/s^2 for vibrations and 1 degree for the virtual pebble for better resolution. Final perception thresholds were determined after five more reversals at the small step size for a total of ten reversals.

During standing trials, each actuation was initiated manually by the experimenter. Subject responses were then recorded and the actuation amplitude was adjusted accordingly. For walking and jogging trials, the actuation procedure was as follows:

1) Actuation: 1 step (actuation automatically initiated 100 milliseconds after heelstrike)
2) Confirmation (no actuation): 2 steps
    a) if the subject answered, "Yes", it meant he felt the actuation
    b) if the subject did not respond, it meant he did not feel the actuation
    c) the actuation amplitude was adjusted based on the 1 up, 3 down algorithm for the next cycle
3) Waiting (no actuation): 2-5 steps (randomized number)
4) Iterate until 10 reversals occur

Test 1 took approximately 30 minutes to complete.

B. Test 2: Identifying Feedback Combinations

As with Test 1, subjects wore the custom shoes, three vibration motors, and sound-blocking headphones. The amplitude of vibration was fixed at 2.0 m/s^2 and the angle of actuation for the virtual pebble was fixed at 35 degrees from the transverse plane. These values were chosen such that all subjects could detect single actuations. They were based on a pilot studies and were tested and confirmed on each subject for this test prior to starting.

Trials were again conducted during three phases: standing, walking, and jogging. During each phase, four single feedback device and six two feedback devices actuations were possible (Tables II and III). Each actuation type was actuated eight times, except any combinations containing either VL or VR, which were actuated four times. Thus, a total of 56 actuations were presented per trial. The order of actuations was randomized.

During testing a green light flashed after each haptic actuation. Subjects were instructed to verbally respond with perceived actuations after the flash. They were free to report any number and any combination of the four haptic devices including the response of no actuation.

During standing trials, each actuation was initiated manually by the experimenter. Subject responses were then recorded and the actuation amplitude was adjusted accordingly. For walking and jogging trials, the actuation procedure was as follows:

1) Actuation: 1 step (actuation automatically intiated 100 milliseconds after heelstrike)
2) Confirmation (no actuation): 2 steps
    a) subjects reported perceived actuations
3) Waiting (no actuation): 2-5 steps (randomized number)
4) Test finished after all 56 actuations initiated

Test 2 took approximately 45 minutes to complete. Two-tailed paired T-tests with Bonferroni correction were used to analyze each combination of two vibration motors against one vibration motor and one virtual pebble combinations.

IV. RESULTS

A. Perception Thresholds

The average absolute minimum threshold values for vibration and the virtual pebble are shown in Table I. The minimum vibration threshold was highest while jogging and virtually identical during standing and walking. 9 of 10 subjects reported higher minimum thresholds while jogging than during standing trials.

Conversely, the virtual pebble minimum threshold was highest during standing and threshold values were very similar during walking and jogging trials. 9 of 10 subjects reported lower minimum thresholds while jogging than during standing trials. Though there seems to be a trend that increasing movement speed leads to decreased sensitivity for vibration and increased sensitivity for the virtual pebble, these trends were not statistically significant in this study.

B. Identifying Feedback Combinations

Subjects consistently found it easier to identify a combination of the virtual pebble and one vibration compared with a combination of two vibrations (Fig. 4). All differences were statistically significant ($p < 0.05$).

For standing trials, subjects correctly identified single feedback actuations with 96.6% accuracy on average. For two feedback device actuations on the foot, subjects perceived combinations with the virtual pebble correctly 52.5% more often than combinations with only vibration, and for knee plus foot actuations subjects perceived combinations with the virtual pebble correctly 38.7% more often than

TABLE I

COMPILED AVERAGE PERCEPTION THRESHOLDS FOR VIBRATION ON THE INSIDE OF THE FOOT (VL) AND VIRTUAL PEBBLE (P) UNDER THE HEEL.

	VL (m/s^2)	P Angle (degrees)	P Height (mm)
Standing	9.1	29.0	8.3
Walking	9.2	21.9	6.7
Jogging	11.6	21.5	6.6

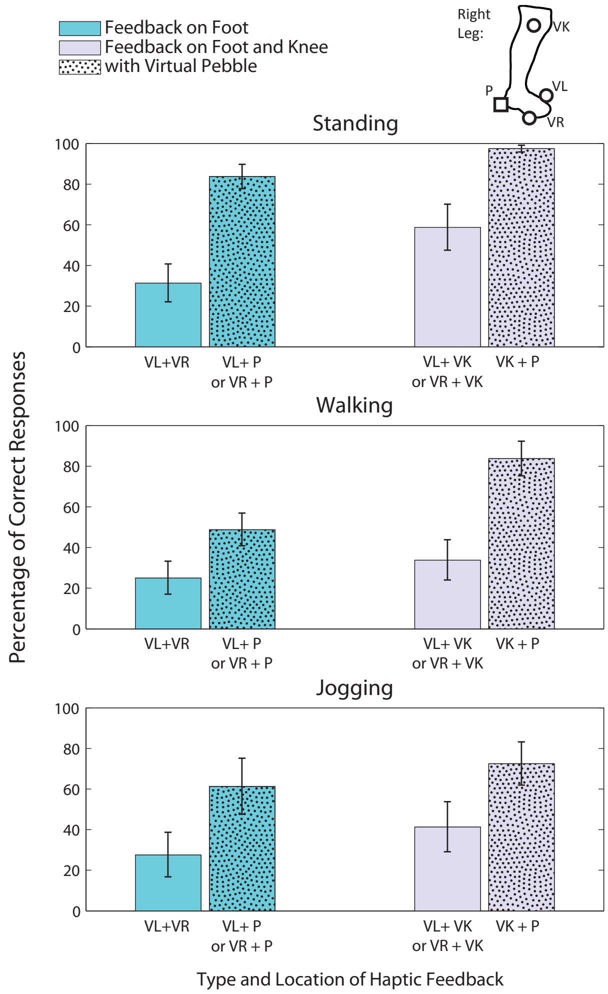


Fig. 4. Identification testing compiled results. For each of the six pairs, subjects more accurately perceived combinations with the virtual pebble, than combinations with only vibrotaction ($p < 0.05$).

combinations with only vibration. Of all combinations, the most accurately perceived was the virtual pebble plus knee vibration at 97.5% accuracy. None of the subjects reported "No Actuation" during standing trials. The confusion matrix for standing trials is shown in Table II.

Walking trials produced similar trends as standing trials with the exception of the reported number of "No Actuations". On average subjects identified single feedback actuations with 84.7% accuracy. Subjects perceived combinations with the virtual pebble correctly 23.8% more often than combination with only vibration for two actuations on the foot and 50.0% more often for knee plus foot actuations. Twenty-eight, or 5%, of all actuations were perceived as "No Actuation" during walking trials. Two of the "No Actuation" reported occured during actuations including the virtual pebble, and the other twenty-six were from actuations only involving vibration. [1]

[1]Due to paper length limitation, the confusion matrix for walking trials is not shown. For more information, please refer to http://bdml.stanford.edu/twiki/bin/view/Haptics/VirtualPebble

Jogging trials results were similar to walking trials. Subjects identified single feedback actuations correctly 91.9% of the time. Subjects perceived combinations with the virtual pebble correctly 33.8% more often than combination with only vibration for two actuations on the foot and 31.2% more often for knee plus foot actuations. Fourteen, or 2.5%, of all actuations were perceived as "No Actuation" during jogging trials. One of the "No Actuation" reported occured during an actuation including the virtual pebble, and the other thirteen were from actuations only involving vibration. The confusion matrix for jogging trials is shown in Table III.

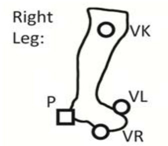
V. DISCUSSION

From the results of this study, it is clear that the virtual pebble provides benefits in perception when multiple tactile actuations occur simultaneously. For combinations of feedback on the foot or on the foot and knee, it was consistently easier for subjects to identify combinations involving the virtual pebble and one vibration as compared with two vibrations. This is likely due to the fact that the virtual pebble can stimulate SA mechanoreceptors whereas vibration primarily stimulates FA-II mechanoreceptors. It appears that subjects find multiple simultaneous stimulations to the same mechanoreceptors difficult to identify. This aligns with previous work showing the deterioration of haptic perception as the number of vibrotactors increases both in stationary [23] and ambulatory tasks [12]. Though the separation distance between haptic actuators appears to provide some improvement such as the distance between two actuators on the foot or one actuator on the foot and one on the knee (compare Fig. 4 VL+VR to VL+VK or VR+VK), using different types of actuators provides a more dramatic benefit (compare Fig. 4 VL+VR to VL+P or VR+P). Combining actuator placement separation *and* differing actuator types should provide the best perception, and indeed subjects found virtual pebble and vibration on the knee (VK+P) to be the easiest of all combinations to identify for standing, walking, and jogging trials (Fig. 4).

It was also evident that the perception deterioration effects due to increased movement velocity, which are common for vibrotactile feedback [7], [12], were greatly mitigated for virtual pebble feedback. One evidence is that during identification testing subjects very rarely reported "No Actuation" when the virtual pebble was part of the actuation combination. While it is expected that subjects would almost always perceive something while stationary, and in fact "No Actuation" was never reported during standing trials, walking and jogging makes perception more difficult. However, only 1.3% of walking and 0.6% of jogging trial combination actuations involving the virtual pebble were reported "No Actuation". In comparison, reports of "No Actuation" for combinations involving only vibrations were 13 times higher than with the virtual pebble. A likely explanation is that small motions in the shoes, clothing, skin, and muscles due to human limb motions, and impact forces between shoe and ground, create extra vibrations not present during stationary testing. These compete with vibrotactile display,

TABLE II

STANDING TRIALS CONFUSION MATRIX FOR IDENTIFICATION TESTING. NUMBERS IN BOLD (ON DIAGONAL) ARE THE NUMBER OF CORRECT RESPONSES. PERCENTAGES ARE SHOWN IN PARENTHESES.

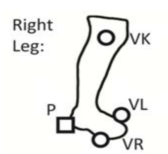


STANDING TRIALS

Subject's Response	Given Haptic Stimulation									
	One Feedback Device				Two Feedback Devices					
					2 Vibr.	1 Vibr. + 1 Pebble		2 Vibr.		1 Vibr. + 1 Pebble
	VL	VR	VK	P	VL+VR	VL+P	VR+P	VL+VK	VR+VK	VK+P
VL	**40** (100.0)	1 (2.5)			31 (38.8)	2 (5.0)		5 (12.5)	1 (2.5)	
VR		**35** (87.5)	1 (1.3)		24 (30.0)		1 (2.5)	1 (2.5)	5 (12.5)	
VK			**79** (98.8)					6 (15.0)	8 (20.0)	1 (1.3)
P				**80** (100.0)		1 (2.5)				
VL+VR		4 (10.0)			**25** (31.3)					
VL+P						**34** (85.0)	6 (15.0)			
VR+P						2 (5.0)	**33** (82.5)			1 (1.3)
VL+VK								**26** (65.0)	5 (12.5)	
VR+VK								2 (5.0)	**21** (52.5)	
VK+P						1 (2.5)				**78** (97.5)
None										
Total Given	40	40	80	80	80	40	40	40	40	80

TABLE III

JOGGING TRIALS CONFUSION MATRIX FOR IDENTIFICATION TESTING. NUMBERS IN BOLD (ON DIAGONAL) ARE THE NUMBER OF CORRECT RESPONSES. PERCENTAGES ARE SHOWN IN PARENTHESES.



JOGGING TRIALS

Subject's Response	Given Haptic Stimulation									
	One Feedback Device				Two Feedback Devices					
					2 Vibr.	1 Vibr. + 1 Pebble		2 Vibr.		1 Vibr. + 1 Pebble
	VL	VR	VK	P	VL+VR	VL+P	VR+P	VL+VK	VR+VK	VK+P
VL	**33** (82.5)	1 (2.5)			39 (48.8)			15 (37.5)		
VR	2 (5.0)	**39** (97.5)			16 (20.0)		5 (12.5)		13 (32.5)	
VK			**71** (88.8)		1 (1.3)	2 (5.0)		5 (12.5)	3 (7.5)	2 (2.5)
P			1 (1.3)	**79** (98.8)		6 (15.0)	1 (2.5)			16 (20.0)
VL+VR	1 (2.5)				**22** (27.5)		1 (2.5)			
VL+P						**27** (67.5)	10 (25.0)	1 (2.5)		3 (3.8)
VR+P						4 (10.0)	**22** (55.0)			1 (1.3)
VL+VK								**15** (37.5)	5 (12.5)	
VR+VK					2 (2.5)			2 (5.0)	**18** (45.0)	
VK+P			1 (1.3)	1 (1.3)			1 (2.5)		1 (2.5)	**58** (72.5)
None	4 (10.0)		7 (8.8)			1 (2.5)		2 (5.0)		
Total Given	40	40	80	80	80	40	40	40	40	80

making perception more difficult. The virtual pebble, by providing low frequency shape information that stimulates slowly-adapting mechanoreceptors as well as fast-adapting mechanoreceptors, is less vulnerable to these effects.

In addition, results from minimum threshold testing showed that subjects were least sensitive to vibration while jogging. This result is again likely due to the increase in vibrations and accelerations that accompany jogging. In contrast, sensitivity to the virtual pebble *increased* as subjects progressed from standing to jogging. In this case, the likely explanation is that impact forces were higher, producing a greater sensation at the site of contact between the virtual pebble and the heel.

A limitation of this study is that we were only able to test three movement speeds: standing, walking, and jogging. A more clear picture of the relationship between ambulation speed and haptic perception for vibration and the virtual pebble would emerge if more walking velocity data points were measured. Additionally, our tests involved a single shoe. In future studies it would be beneficial to tests subjects with a variety of shoe sizes.

Future work should focus on improving the virtual pebble design to make it more robust and accessible to a larger audience. Ideally, the virtual pebble should be completely embedded in a heel insert. The insert could then be easily transferred to different shoes. While the servo motor used in the current virtual pebble is small it may need to be even smaller to fit inside a heel insert. Alternative actuators, such as shape memory alloys or bi-stable motors, could be smaller and consume less power. Embedding a small battery, force sensing resistor, and wireless communication chip would make the virtual pebble insert completely contained. Such a haptic device could be configured to communicate with a smart phone or other portable computing device.

VI. CONCLUSION

In active exercises such as walking and jogging, user perception accuracy decreases when multiple vibrational feedback devices are used simultaneously. This research introduced the virtual pebble, an alternative haptic display embedded in a shoe insole. The virtual pebble stimulates both slowly-adapting and fast-adapting mechanoreceptors to provide greater perception distinction from typical vibrotactors, which primarily stimulate FA-II mechanoreceptors. Our user perception study demonstrated increased user perception accuracy for standing, walking, and jogging when using a combination of a vibrotactor with the virtual pebble, versus a combination with two vibrotactors. These promising results provide an opportunity for dynamic movement training with multiple haptic feedback devices, with applications that include human gait retraining for osteoarthritis and cerebral palsy patients.

VII. ACKNOWLEDGMENTS

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