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Rendering Perceived Terrain Stiffness in VR via Preload Variation Against Body-weight

Wooje Chang, Seungwoo Je, Michel Pahud, Mike Sinclair, and Andrea Bianchi

***Abstract*—*PreloadStep* is a novel platform that creates the illusion of walking on different types of terrain in Virtual Reality without requiring users to wear any special instrumentation. *PreloadStep* works by compressing a set of springs between two plates, with the amount of compression determining the perceived stiffness of the virtual terrain. The platform can render perception of stiffness by applying preload forces up to 824 N in different portions of the terrain, capable of changing stiffness illusion even while a user is standing on it. The effectiveness of *PreloadStep* was tested in two perception studies (perception thresholds and haptic-visual congruence studies) and an example application, with the results indicating that it is a promising method for creating engaging virtual terrain experiences.**

***Index Terms*—Stiffness-display, haptics, terrain, VR.**

I. Introduction

Recent research explores different methods to increase the realism of and the engagement with the environment of Virtual Reality (VR) applications. Previous work on shape-changing displays recreate geometric features of terrains that are perceived by users when they walk over them, such as terrain irregularities [1], [2], variations of height [3], [4], or even the details of objects placed on the top of the surface (e.g. stones [1] or furniture [5]). They take forms of terrains [1] or walls [6], creating terrains of increasingly higher resolutions [1], [2], [7], [8], seemingly endless terrains via specialized mechanical platforms [3], [4], [9], or even physical walls operated by people [10]. Some other projects explored the vertical dimension by employing passive edges [11], [12] or mechanized elevation [3], [13]–[15] to recreate structures like stairs and obstacles.

However, these shape-changing displays are limited to geometric features of terrains. Haptic-feedback displays, in forms of platforms [16]–[18] and wearables [19]–[21], attempt to render the materialistic characteristics to recreate the illusion of walking on terrains made of sand or snow. Platforms utilizing vibrotactile feedback [16], [17] or motor torque [18] circumvent this, but the rendered experiences are limited to scenarios with relatively small compliance deformation where the user's foot does not break and dig into a surface. Wearables are able to describe a wider range of materials, using vibrotactile actuators [19], magnetorheological fluids [20], pneumatic bladders [22], [23], or propellers attached to the calves [21], but they require instrumenting users.

We propose a novel platform—*PreloadStep*—that allows a user to perceive terrain materials with relatively large compliance deflection without requiring user instrumentation via wearables. We achieve this by applying a varying amount of preload against the user as they step onto the platform, creating an illusion of variable stiffness. We compress a set of springs between a pair of plates—the higher the compression of the springs, the greater the preload, and the stiffer the rendered material feels. This mechanism allows for scaling up to a 4-step, 120 cm long terrain design that can achieve five levels of perceived stiffness.

In this paper, we present the mechanism's principles of operation and implementation. We then conduct a Just Noticeable Difference (JND) perception study to measure the stiffness thresholds for whole-body interactions, followed by a study exploring pseudo-haptics on how visual cues in VR alter these perception thresholds. We then present a pilot study with an example application to gather qualitative insights about the perceived realism, enjoyment, difficulty, and engagement of walking over our system.

II. Platform overview and implementation

PreloadStep is a haptic-feedback platform that can render stiffness characteristics and the bounciness of a virtual terrain. It achieves the illusion of variable stiffness by applying preload forces against the user during initial contact, exerted by a spring platform following the Hooke's Law, $F_s = -kx$. The platform employs four springs (41.2 N/cm each, for a total of k = 164.8 N/cm) sandwiched between two rigid wooden layers, where the top layer (i.e., the *surface layer*) translates downward whenever a user steps on it (see Figure 1). The bottom layer (i.e., the *spring compression layer*) is vertically positioned by a motor, changing the compression length of the springs (x) against the top layer to change the preload force and create an illusion of change in stiffness.

A. Implementation detail

PreloadStep measures 60 cm (width) × 120 cm (length) and consists of 4 individual steps, each measuring 60 cm × 30 cm and capable of a 5 cm vertical displacement (compression), which corresponds to exerted preload forces in the range of

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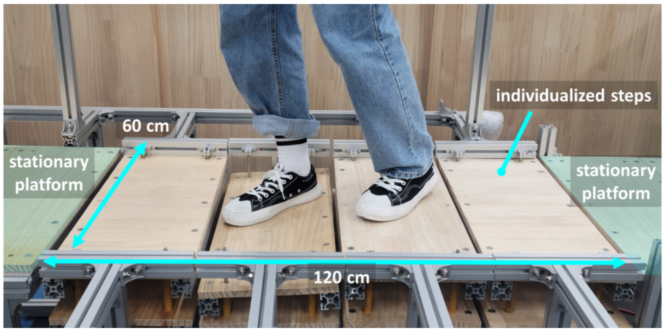

Fig. 1. *PreloadStep* is made of four individualized steps that can change its stiffness illusion via preload force with users standing on top of it

0-824 N. The springs with this force range were selected on factors of maximum safe compression (5 cm compression range was chosen via in-lab testing where possible tripping could be minimized while wearing a VR headset), spring constant (previous work suggests that values above 242 N/cm could be deemed as solid surface [24]), and durability (die-casting springs can reliably withstand repeated large loads). A side-by-side comparison of the platform with no preload and full preload is shown in Figure 2. The maximum preload rendering time (for full stiffness illusion, changing from the minimum) is 10 seconds.

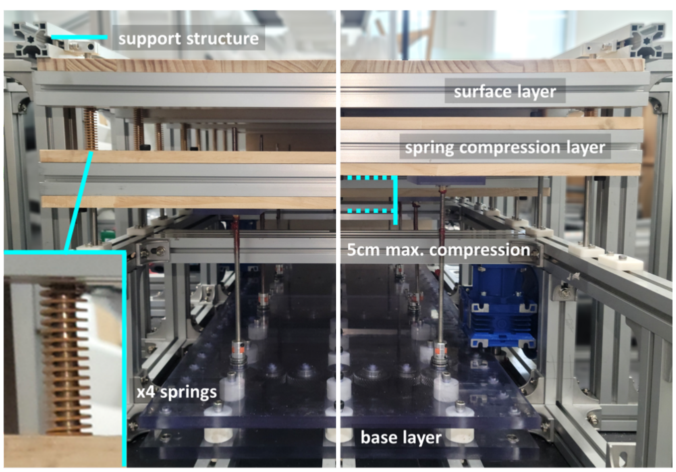

Fig. 2. A close up view of a single step of *PreloadStep*—left: fully soft (not compressed) state; right: fully stiff (compressed) state

Each step is driven by a pair of 8mm lead screws with the lead and the pitch of 2 mm. As they rotate, these lead screws move the brass nuts attached to the spring compression layer, moving it vertically along the screws to compress the springs (four 100 mm, 41.2 N/cm mold springs) to the desired length against the surface layer. The surface layer pushes against the aluminum extrusion structure holding the entire system together, forming an even interaction surface. This layer supports the user's weight with deformation movements reflecting the material stiffness.

The lead screws are attached to a gear layer consisting of two rows of 29 30/40-tooth helical gears embedded between two 15 mm thick polycarbonate sheets measuring 70 cm by 120 cm. A 750 W, 24 V, 3000 RPM motor with NMRV040 worm gearboxes of 15:1 gear ratio drives each row of gears, powered by a 24 V, 125 A Meanwell RSP-3000 power supply with a 60 Ah 24 V lithium-ion battery placed in parallel acting as a bypass capacitor. The motors are driven by Cytron SmartDriveDuo-60 motor driver, controlled by an Arduino Uno receiving commands via serial communication from the main PC running a custom Unity application written in C#. The Arduino also receives each step's compression layer position data from a set of linear potentiometers. The gears are connected such that each motor drives two alternating steps. This configuration was designed to minimize the cost of the motors (i.e., using two motors instead of four), and the VR environments have inconsistent terrain stiffness matching the platform's pattern.

The platform is complemented by an HTC Vive Pro[1] system consisting of a VR headset, a Vive controller, and a pair of Vive trackers. The trackers are used to calibrate and detect the user's feet position as done in previous work [1], which are tracked by the custom Unity program. These data are used for producing visual effects, if necessary, when users step onto the platform. The system overview combining the platform, the control system, and the VR system is shown in Figure 3.

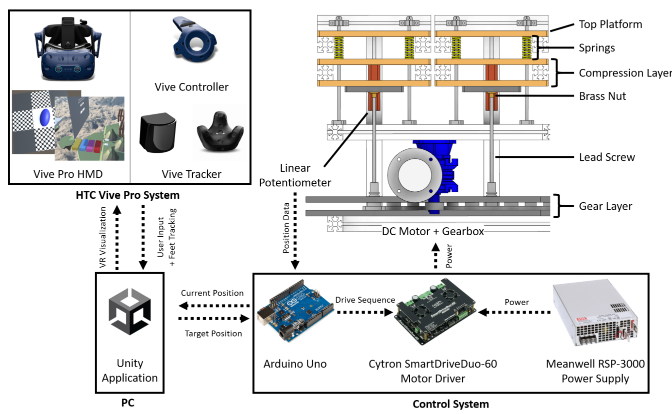

Fig. 3. The system consists of the *PreloadStep* platform, a main PC running a Unity application, an HTC Vive Pro system, and the control system

III. User Studies

Using the *PreloadStep* platform, we sought to identify 1) the Just Noticeable Difference (JND) values of stiffness perceived via the system, 2) the visual-haptic relationship when providing visual stimuli in VR discordant from the rendered forces, and 3) the applicability of the system in relation to expressing VR environment. The first two points are explored via two user studies, motivated by previous literature on psychophysics that explored different forces and perceptions involved in people's movement [25]; we extend this line of research to establish the psychophysics involved in whole-body interaction with the floor. Point #3 was explored by creating a working VR application and conducting a VR study to gather the users' experience of the VR environment with the platform. All studies took approximately one hour each involving 12 participants, and each participant signed a

[1]https://www.vive.com/us/product/vive-pro/

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consent form and was compensated with ∼10 USD in local currency.

A. Study 1: Perception Threshold of JND

To determine the number of distinct levels of stiffness rendered by the platform that can be correctly perceived by standing users, we conducted a perception threshold study (JND) that closely follows the setup and method introduced [25] and explored for handheld variable-stiffness display [26] in previous work. However, while previous work observed subjective perception differences of stiffness for different floor/ground materials when using whole-body weight [27], [28], these did not quantify the actual forces necessary to vary the perception thresholds. Thus, our JND study uses the method of constant stimuli [29] to find the minimum preload force with respect to the user's body weight needed to be applied to create a noticeable difference in floor stiffness perception.

1) Setup: Twelve healthy participants (5 female, age: 20-27, M = 24.2) without movement impairment were recruited for this study from our institution via a bulletin board and word-of-mouth. For the hardware, we used only a single step of the *PreloadStep* platform described above. Each participant was asked to stand on a stationary platform placed adjacent to the first step of the *PreloadStep* system, allowing users to easily step on and off the actuated platform. Curtains were placed around the user to eliminate any visual cues that could aid the discrimination of stiffness (i.e., vertical displacement). Another curtain was placed horizontally across the first step at the waist height to further remove any cues about the foot's visual placement. Finally, the participant wore a pair of noise-canceling headphones and held a wired numpad to record responses. The physical setup is shown in Figure 4.

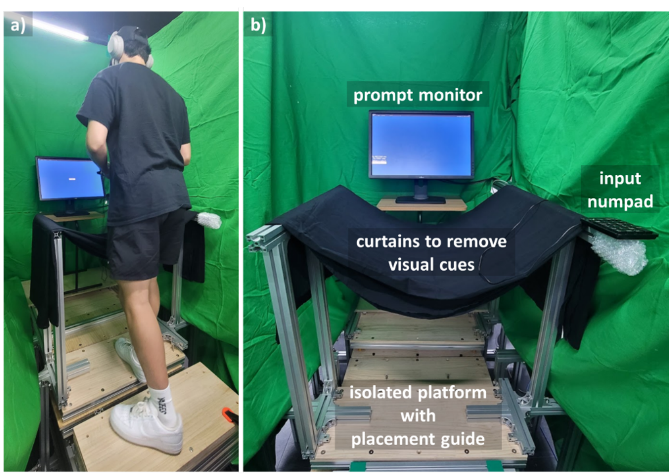

Fig. 4. a) A participant participating in the JND study; b) The setup eliminates visual cues, leaving only the prompt monitor in the field of view for instructions

2) Procedure: The first step in the platform was actuated using two different stiffness levels. For each level, participants were asked to place a foot on the platform and to indicate which of the two conditions felt softer. One condition was the baseline condition of preload force equivalent to either 25%, 50%, 75% of the user's body weight and the other was the value of the baseline condition offset by ±7.5, ±15, or ±22.5%. These values were predetermined from a pilot study performed beforehand and after having measured the user's weight with a scale. The study consisted of 108 trials (3 baselines × 5 blocks × 12 trials), with trials randomized within each block. There was no limitation on the amount of time taken per trial, and the participant took optional breaks between baseline conditions. We enforced a minimum of two steps to be taken before each response, which were recorded in a custom Unity application coded in C#.

B. Study 2: Visual-Haptic Congruence Perception

Previous research indicates that the visuals greatly affect the perception of haptic properties of objects people interact with [30], [31]. We conducted a visual-haptic study to find if similar effects hold in terrain stiffness, observing the potential effects of visual redirection (shown in Figures 5a, 5b) on the perception of softness and haptic-visual congruence.

1) Setup: A different group of twelve healthy participants (5 female, age: 21-27, M = 23.9) with no restrictions in movement were recruited for this study. Each participant stood on the same stationary platform placed adjacent to the first step of the *PreloadStep* system, wearing a Vive Pro headset and a pair of noise-cancelling headphones. A Vive tracker was placed around the participant's dominant foot to display its position in a custom VR application. The participant navigated the VR application with a controller using their dominant hand. The physical setup is shown in Figure 5c.

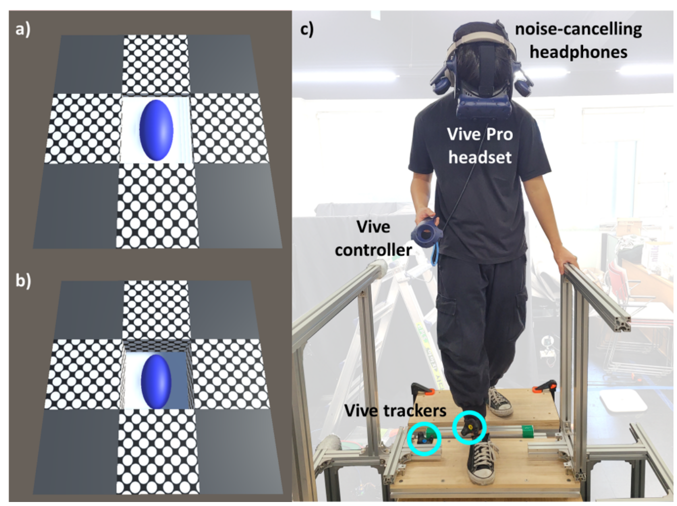

Fig. 5. a) Movement of the virtual platform being pushed down 1 cm with Visual Multiplier of 1; b) with VM of 18; c) Visual Study Setup

2) Procedure: The participant placed a foot on the first step of the virtual platform in front of them, seeing visual feedback of their tracked foot in the VR headset. The visual feedback was programmed such that the planar position of the foot corresponded to the actual physical position on the platform, but its vertical displacement was visually redirected in VR. This visual redirection was determined using a Visual Multiplier (VM) of 0, 1, 3, 6, 9, 12, 15, or 18—similar to the C/D-ratio explored in previous work [32]. In practice, if the participant's foot actually moved 1 cm down the platform

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because of the softness of the step, this displacement appeared to a user in the *VM = 15* condition as a 15 cm downward movement of the foot.

After experiencing each trial, the participants were asked to rate on a 7-point scale with the ends labeled how soft the platform was perceived, and how well the experienced stiffness matched with what they saw. The trials explored across preload forces of 0-80% of the user's body weight with an increment of 20%, which is higher than the JND value. The overall study consisted of 80 trials (2 blocks × 8 VMs × 5 preloads), with trials randomized within each block. There was no limitation on the amount of time taken per trial, and the participant took optional breaks between blocks. We enforced a minimum of two steps to be taken before each response, which were recorded in a custom Unity application.

IV. Results

A. JND Study Results

The JND across all conditions is calculated by fitting a cumulative distribution function to the data (Figure 6). The function

$$1 - \frac{1}{1 + e^{-a(x-b)}} \tag{1}$$

where $a = 0.10477845, b = -0.83061443$ represents the expected distribution of responses as discussed in [25]. The distance between the baseline and the threshold—defined at the 84 percent mark—is the computed JND value. The result for the *PreloadStep* system is a JND of 18.2 percent of the body weight. This result means that there is a maximum of five discrete levels of uniquely perceived stiffness that can be rendered by the platform for discrete steps that are raised above the surface level before making contact again.

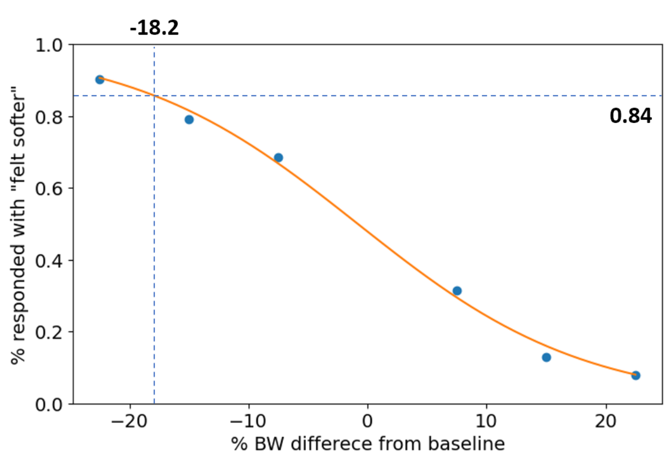

Fig. 6. Psychometric curve of the JND study results show a logistic regression relationship with the JND value of 18.2 percent of the user's body weight

B. Visual-Haptic Study Results

We performed a Kruskal-Wallis test on the response of the questionnaires and found that there is a significant difference among groups for both Stiffness (H(2) = 31.119, p < 0.001) and Visual-Haptic Congruence (H(7) = 199.571, p < 0.001). Post-hoc comparisons using a pairwise Dunn test indicate that there is a statistically significant difference in the level of perception for stiffness when using the VMs with values of 15 and 18 (7a). Furthermore, results also reveal significant differences for the haptic-visual congruence levels among all test conditions higher than the baseline case (Figure 7b).

The near-vertical user point of view may account for the high VM values; for relatively smaller VM values, the users do not seem to be able to notice a significant difference from the baseline condition. In fact, the congruence results seem to indicate that the mental baseline for what is considered natural may be in the mid-range (6, 9), as suggested by the significant difference in congruence between VM of 6/9 and 18. Noting the declining congruence levels as VM approaches more extreme values, the effect might subside for higher VMs.

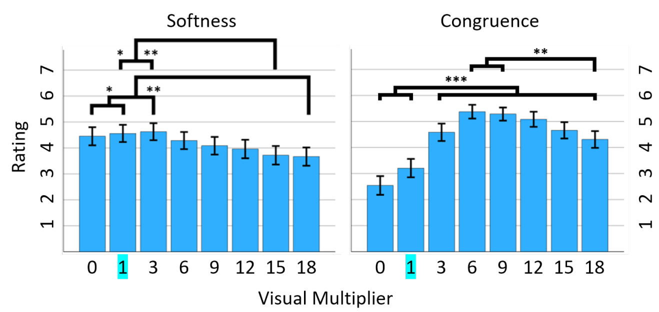

Fig. 7. Visual study post-hoc Dunn test results—highlighted is the baseline condition of Visual Multiplier 1; $***$ for $p < 0.001$, $**$ for $p < 0.01$, $*$ for $p < 0.05$

C. Summary of Results

The results from our two studies can be summarized as follows:

- The *PreloadStep* platform can uniquely render five distinguishable levels of stiffness.
- The Haptic-Visual congruence increases for VMs higher than 1—this means that exaggerated movements feel more aligned with the perceived haptics.
- The perception of stiffness decreases (i.e. feels less stiff, or more soft) for VMs 15 and 18.

V. Application in VR

In order to evaluate the system's efficacy in augmenting the users' VR experience, we tested it and collected measures about perceived realism, difficulty, engagement, and enjoyment. We designed a VR application scenario (shown in Figure 8) in which a user is stranded on an island and needs to collect fruits from another island by crossing a set of floating steps. Different from our previous studies, this application requires users to walk back-and-forth across the *PreloadStep* system five times, under two haptic conditions with VM of 3—baseline condition of maximum preload applied (simulating a fully hard surface) and a test condition of the preload set to a fixed level of 25% of the user's body weight. After each condition, the participants were asked to rate on a 7-point scale

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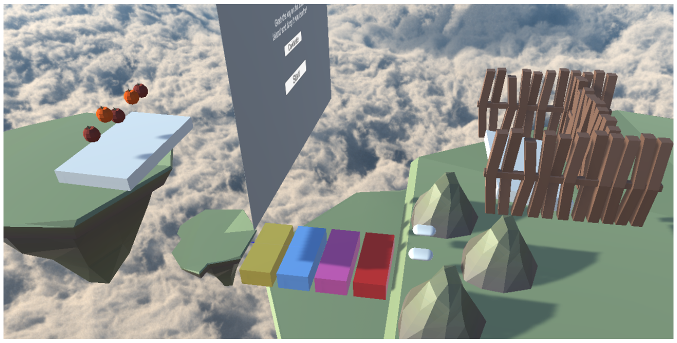

Fig. 8. The user has to cross floating docks to retrieve fruits, stepping on the platform under two conditions

the realism, difficulty, engagement, and enjoyment involved in the task.

Twelve healthy participants (5 female, age: 22-28, M = 24.8) with no restrictions in movement tried out the application using a Vive Pro headset. They wore a pair of noise-canceling headphones and a pair of Vive trackers on their feet, and they navigated and interacted with the VR environment with a controller held in their dominant hand.

A. Results

The participant response results are shown in Figure 9. We performed a Friedman test and found that there was a significant difference in participant rating between the baseline and the test conditions ($\chi^2(7) = 52.100, p < 0.001$). Following up with a pairwise analysis using Wilcoxon signed-rank test with Bonferroni-adjusted significance level of $\alpha = 0.0125$, we find that the participants reported significantly higher ratings in realism ($Z = -2.848, p = 0.004$), difficulty ($Z = -2.611, p = 0.009$), engagement ($Z = -3.024, p = 0.002$), and enjoyment ($Z = -2.953, p = 0.003$) when softness illusion was presented. This increase indicates that the system is capable of producing a more immersive experience with the VR application, congruent to previous work exploring similar metrics [1], [14], [21].

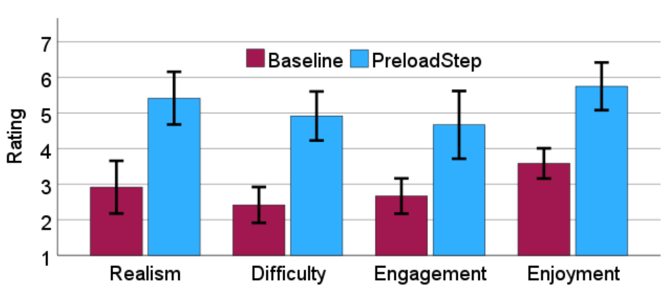

Fig. 9. Participants rated realism, difficulty, enegagement, and enjoyment higher when softness illusion was present. The error bars indicate 95% confidence intervals.

VI. Discussion

From the JND study results, we find that five levels of distinct stiffness can be rendered with *PreloadStep*. We also find that the perceived stiffness level can be further shifted using visual redirection, changing perception of material characteristic via pseudo-haptics congruent to previous work [31]. We could combine the effect of these two findings to overcome technical limitations of the device, similar to previous work on object weight perception [32]; a desired softness can be achieved faster with a combination of both visual and haptic feedback, and the softness outside of the range capable with the device can be achieved. This would allow faster rendering rate, making it unnecessary to render stiffness in the full operating range, but rather relying on the illusion conveyed by the haptic-visual congruence.

Second, our work is uniquely capable of walking on top of the platform and changing the stiffness of the material at the same time. While previous work [1] is limited to walking after the shape transformation is finished, *PreloadStep* expands the immersive VR haptic experience with a dynamic material platform. We see an opportunity of combining a shape-changing display like in [1] with our stiffness-changing platform for delivering a whole terrain VR experience to users.

Finally, we can further extend the effects of the platform outside of direct association with the materials and onto the whole-body experience. From the user responses to the application, we find that the participants perceived an increase in difficulty when the terrain became softer, even though they were performing the same task. Similar to previous work that used the perceived heaviness of a head-mounted display to gamify a VR experience [33], we also see an opportunity to leverage the user's fatigue to create a new type of experience in which carrying out a particular whole-body interaction becomes more challenging.

VII. Conclusion

This paper presents a method for enhancing interaction with VR terrains by manipulating the preload forces applied against the user standing on the platform to create the illusion of varying stiffness. A JND study reveals that users can reliably distinguish five different degrees of stiffness with our platform. We then tested the effects of exaggerated visuals on the haptic perception of stiffness via a congruence study and found that the haptic-visual congruence indeed increased when the visual feedback was exaggerated and softness perception changed for highly exaggerated visuals. Using these findings, we suggested a potential application applied to VR, where the users were free to walk across the platform under two haptic conditions. Our findings show that the participants found the rendering of stiffness particularly more realistic, difficult, enjoyable, and engaging while performing the same task.

A. Limitations and Future Work

Although *PreloadStep* is capable of rendering dynamic terrain properties while a user simultaneously stands on it, our hardware platform also presents numerous limitations. For one, the system's dimensions are limited to a 1-dimensional platform with relatively largely sized steps. Furthermore, the current prototype only has 4 steps, each capable of applying a preload of 824 N max. We recognize this limitation but at the same time emphasize that the system we constructed is relatively modular, and it is simple to add motors to increase the length of the platform (e.g., see the fixed steps attached to the platform shown in Figure 1). The rendering speed can be limiting (in part due to each motor being connected to an alternating set of steps), but for applications involving no large changes in a shorter amount of time (less than 2 seconds), manipulation of the VM can serve as a placeholder while the system is undergoing changes. Future work could focus on exploring and testing larger and faster platforms using a more efficient transmission system than gears. Also, we have not explored VM values between 0 and 1; while future work could explore this, we note the lack of significant difference between 0 and 1 suggests that the difference in perception would be minimal. Finally, this paper only presents a single application, and future work will need to enrich the interaction space and test the effectiveness of rendering different terrain materials in a wider set of applications.

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