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Biomechanically-Consistent Skin Stretch as an Intuitive Mechanism for Sensory Feedback: A Preliminary Investigation in the Lower Limb

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Biomechanically-consistent skin stretch as an intuitive mechanism for sensory feedback: a preliminary investigation in the lower limb*

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Abstract—**The proprioceptive loss accompanied by lower limb amputation can impair function and mobility. We explore a simple, mechanical skin-stretch array configured to generate superficial tissue behaviour that might occur with movement about an intact joint. Four adhesive pads attached around the circumference of the lower leg were connected via cords to a remote "foot" mounted on a ball joint attached to the underside of a fracture boot, such that "foot" reorientation would result in skin stretch. In two discrimination experiments performed with and without the connection, with no view of the mechanism, and with minimal training, unimpaired adults (i) estimated foot orientation following passive foot rotations (eight directions), either with or without contact between the lower leg and boot, and (ii) actively lowered the "foot" to estimate slope orientation (four directions). In (i), 56-60% of responses (depending on contact condition) were correct and 88-94% were either correct or one of the two adjacent choices. In (ii), 56% of responses were correct. In contrast, without the connection, participants performed near or no different to chance. A biomechanically-consistent skin stretch array may be an intuitive means to convey proprioceptive information from an artificial or poorly innervated joint.** **Keywords: rehabilitation; haptics; proprioception; modality-matching; sensory feedback; prosthetics; skin stretch; wearable; lower limb**

I. Introduction

Proprioception relays our body positions as we move, providing the opportunity to correct, adjust, and redirect motion as we interact with our environment [1]. During an isolated step, the proprioceptive sense of a greater ankle dorsiflexion at foot contact, for example, would also infer that the ground beneath the foot at that instance is sloped upwards, prompting an alteration to the push-off or limb clearance strategy. The perception of greater limb extension prior to foot contact with the ground may infer a step downwards and, with it, the requirement to arrest momentum to a greater extent. As locomotor dynamics must be modified for different walking contexts, proprioceptive afferents appear vital for robust and adaptive locomotion. This sense, a loss of which is known to drastically impair function and mobility [2], can be reduced due to neuropathy [3] and is absent from prosthetic joints.

While structural restoration following lower limb amputation may be possible using a prosthesis, there remains a disconnect between the artificial extremity and the rest of the body. Although a prosthetic foot and ankle or knee joint may be designed and configured to mimic biological motion in a particular context, information on its movement is not directly relayed to the prosthesis user. Clues about limb position and loading may be attained when there are perceptible changes in the pressure distribution and moments induced at the socket-residuum interface, however, a lack of afferent information regarding prosthetic joint position and behavior may hinder the appropriate organization of movements at other joints given changing external locomotor task demands. As an example, a lack of knee proprioception will affect the ability of the prosthesis user to determine with confidence when the joint is sufficiently extended to prevent limb buckling on foot contact, leading to anxiety and inefficient compensatory strategies [4].

A means to restore proprioception when it is degraded or lost may improve mobility in a wide range of environmental contexts for people with amputation and neuropathy alike. However, in comparison to the body of work directed towards haptic sensory supplementation for the upper limb [5], little attention has been paid to non-invasive solutions for lower limb loss. Further, proprioception has been targeted scarcely; the predominant focus being on relaying tactile information from the plantar surface of the foot to sensory arrays mounted elsewhere on the body, e.g. thigh, or trunk [6, 7]. Successful restoration of proprioceptive sense requires meaningful aspects of limb posture and movement to be relayed synchronously and in an intuitive manner [8]. Modality-matching, which infers maintaining congruence between the feedback and the physiological mechanism behind the stimulus or action of interest, is desirable [8] but difficult to achieve non-invasively for proprioception. Haptic feedback mechanisms designed to convey information about knee angular position and/or motion have employed vibrotactile or electrotactile stimulation at remote locations such as the lower back [9] or hip [10], i.e., non-matched modalities at sites that do not relate instinctively to the action of the joint.

Soft tissue deformation may be readily exploitable as a medium for sensory supplementation, and may be harnessed in a manner that adheres to modality-matching principles. While segments of the body are often analyzed biomechanically as rigid bodies linked by joints, many soft tissue structures extend across segments, including muscles, fascia, skin and subcutaneous tissue. These structures necessarily deform as segments rotate about each other, and often reciprocally across the joints (e.g., posterior structure loosens as anterior structure tightens; Fig. 1). The direct attachment of external devices to muscle, cineplasty, has been shown to provide the individual with upper limb amputation both control of the position of the extremity and the sensation of its movement, by leveraging the force production and sensory capabilities of the biological muscle and tendons [11, 12]. Exploring afferent feedback alone, the attachment of a

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mechanical hand to the palmaris longus tendon was shown to facilitate discrimination of grasped object size with 80-100% accuracy [12]. More recently, integration of these concepts into agonist-antagonist muscle pairs has shown promising results in people with lower limb amputation [13]. However, it is possible that a similarly intuitive effect perceptually may be achieved at superficial level, without surgical intervention, by targeting cutaneous mechanoreceptors responsive to skin stretch that contribute to joint position sense [14]. For example, with knee flexion, the skin anterior and proximal to the knee will stretch, whereas that posterior and proximal to the knee will loosen (Fig. 1). Using a direct, mechanical connection to mimic this, skin deformation, and the sensory afferents associated with it, would occur both immediately and in a manner relevant to the change in posture; addressing two components important in the delivery of intuitive feedback.

Skin stretch transducers are gaining momentum as haptic devices due to a high degree of skin sensitivity to tangential forces [15] alongside potential illusory benefits [16, 17] In the upper limb, the use of skin stretch has been investigated to aid forearm guidance [18], determination of hand aperture [19], and for differentiation of gripped object size [20] and stiffness [21]. Further supporting the current direction of enquiry, Akhtar et al. showed that by directly linking the digits of an artificial hand to skin stretch transducers on the forearm, prosthetic finger flexion angle could be discriminated with similar accuracy to an equivalent experimental arrangement with a vibrotactile array, but requiring minimal power and less surface area [20]. In the same study, in discriminating different grip apertures, the training duration was shorter with skin stretch in comparison to that with a vibrotactile array [20]. In the lower limb, a high perceptibility to lateral skin stretch has been demonstrated in people with and without amputation [22, 23]. Lower limb skin stretch feedback applications are sparse, however. Feedback via skin stretch has been explored for foot contact detection [23], but its potential for relaying proprioceptive information has not been fully exploited.

The aim of this initial proof of concept work was to explore whether biomechanically-congruent skin stretch could be used to infer the position of an artificial joint, with limited training. Using a system of cords adhered proximally to the skin, extending distally past a joint to an artificial extremity, we aimed to invoke an immediate, biomechanically-relevant skin stretch sensation as the posture of the artificial joint was changed. Our overarching hypothesis was that people would be able to determine joint posture based on the pattern of sensation evoked on the skin of the limb to which the joint was remotely attached.

II. Methods

A. *Experimental device and design*

The test device comprised of an artificial "foot" mounted on a ball joint that was attached to the sole of the frame of a rigid medical fracture boot (Short Cam Walker, United Ortho, Fort Wayne, IN, USA) beneath an approximate ankle joint center (Fig. 2a). Four adhesive pads (50.8 x 50.8mm; Self-adhesive electrodes, Angel) were attached around the circumference of the lower leg, measured to lie proximal to the boot and distal to the knee, at anterior-medial, anterior- lateral, posterior-medial and posterior-lateral locations. These were connected to the "foot" via non-elastic cords (Black Waxed Cord, The Paper Studio), tied to holes at corresponding locations at a fixed distance from the ball joint. Rotation of the "foot" about anterior-posterior and medial-lateral axes caused the pads to draw on and release the skin (Fig. 2a, supplementary video). Participants had no prior observation of the testing set-up and were unable to see the equipment in situ.

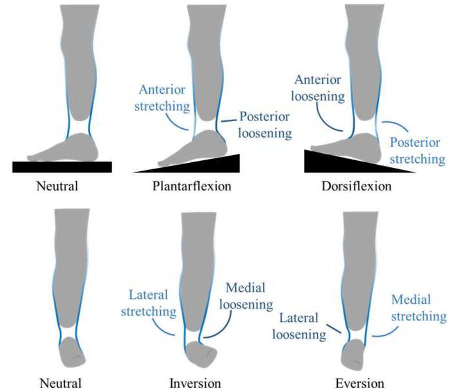

Figure 1. Effect of foot orientation on soft tissue deformation.

After attachment of the pads, the right limb of the participant was placed into the boot frame in one of two configurations. In the primary configuration (Fig. 2b), padding was applied around the leg and beneath the heel of the foot to reduce forefoot contact, and strapping used to secure the leg in place. In the secondary configuration (Fig. 2c) the foot was supported within, but did not touch, the frame of the boot. The secure contact between boot and limb in the primary configuration allowed additional cues as might be experienced at the prosthetic socket-residual limb interface, whereas the secondary configuration eliminated those cues, allowing the technique to be assessed in isolation. Tests were performed in two conditions: *connected* and *unconnected*, with order alternated across consecutive participants. In the *connected* condition, the cords were clipped to the pads using cord locks, and adjusted to apply light tension to the skin at all locations; emulating a pre-stress in a neutral position and permitting reciprocal loosening during joint movement. Prior to testing, due to anticipated variance in skin stretch sensitivity at the different locations on the leg, the artificial foot was manually rotated around all testing postures at maximum range of motion, and the participant asked whether "the pull at any pad felt weaker or stronger". The cords were adjusted until the participant reported that the sensations felt equal. In the *unconnected* condition, the pads were affixed to the limb but the cords were not attached to them.

This research was divided into two broad experiments. Experiment 1 was conducted supine with passive motion of the joint, and sought perceptual judgements on the orientation of the "foot" when manually rotated by the assessor. Experiment 2 was conducted in standing, and explored participants' perceptions of the direction of the slope of the ground when actively lowering the limb and "foot" onto a 15° slope. The displacement range of each of the pads was ~20 mm.

B. *Participants*

Fourteen right-handed adults, aged 18-40, with no self-reported medical condition that would affect the outcome of the experiment were recruited from the student body at Northwestern University, and provided written informed

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consent to participate. All completed Exp. 1 and eight returned for Exp. 2 approximately three months later.

C. *Experiment 1 – Foot orientation perception*

Participants completed the experiment in either the primary configuration (Exp. 1a; n = 7; 5F, 2M; mean (SD) 23.0 (2.0) years) or secondary configuration (Exp. 1b; n = 7; 5F, 2M; 23.7 (2.1) years). They lay supine on an examination bench and wore glasses that blocked their vision of their body, legs and feet. A model of a right foot was mounted on a ball joint above the torso for registering responses (Fig 2b). The participant was asked to "move the model to match the direction the [artificial] foot moved in" using the model foot, gripped in both hands about its center of rotation. To ensure participants understood the task and could generate appropriate responses, manipulations were first tested using the participants' own right foot. The participant's foot was manually moved by the investigator from neutral into one of four primary joint postures (dorsiflexion, plantarflexion, inversion and eversion; described to the participant as *toes- up*, *down*, *in* and *out*, respectively), then in the four intermediate postures (dorsiflexion-inversion, plantarflexion-eversion, plantarflexion-eversion, plantarflexion-inversion; described as *up-and-in*, *up-and-out*, *down-and-in*, *down-and-out*; Fig. 2d). All participants were able to produce the correct responses and progressed to the experiment, for which the designated test configuration was applied.

In both conditions (*connected*, *unconnected*), the tests began with training, which lasted ~5 minutes. Participants provided responses when the foot was moved in the four primary directions (12 trials), and then in all eight directions (24 trials) with order randomized. Knowledge of results was provided after each individual trial and, if incorrect, the participant was informed of the correct response. Participants then completed three sets of 24 test trials with no feedback, with a short break between each set. All practice and test trials were then repeated in the second condition.

D. *Experiment 2 - Perception of slope underfoot*

Participants (n = 8; 6F, 2M; 23.9 (2.2) years) wore the test device on their right leg in the primary configuration, and stood with their left leg on a raised platform. They were asked to lower their right leg until the "foot" contacted a slope underfoot and then to raise the leg before producing a response. Perceptual judgments of the direction of the slope beneath the "foot" were signaled by moving a palm board beneath the right hand (Fig. 2e,f; "I'd like you to move the platform [palm board], so it matches the direction of the slope under your foot."). Only the four primary directions (invoking dorsiflexion, plantarflexion, inversion, eversion; described as *uphill*, *downhill*, *inwards* and *outwards*, respectively) were tested, to prevent fatigue.

For practice purposes and to ensure the participant understood the test procedure and instructions, the participant first made perceptual judgments lowering their own foot onto the sloped surfaces. Then, after the test device was secured to the right limb in the primary configuration, they sat with the "foot" resting on a 3cm tall, lightweight trolley. The limb and trolley were moved passively by the assessor, and then actively by the participant, in anterior-posterior and medial-lateral directions, and in a circular pattern. These movements caused the angle between lower leg and "foot" to change; altering the tension of the cords in a manner relevant to the movements. During this familiarization procedure, which lasted ~1-min, participants were asked to focus on the sensations they experienced in their lower leg. Again, no view of the test equipment or configuration was permitted.

Three test sets of 24 trials were completed in the two experimental conditions (*connected*, *unconnected*) with condition randomized and direction order (*uphill*, *downhill*, *inwards*, *outwards*) block randomized in groups of eight trials. Unlike in Exp. 1, no feedback was provided regarding response accuracy. Rest breaks were taken every 12 trials. The first three participants were given no specific information about what to focus on when making perceptual judgments. It became clear from the comments of two of three participants that it was not obvious that sensations at the locations of the adhesive pads were to be used to make judgments in the *connected* condition. To remedy this, participants 4-8 (4F, 1M; mean (SD) 24.8 (2.4) years) were explicitly prompted to "focus on the sensations at the pads" in the *connected*

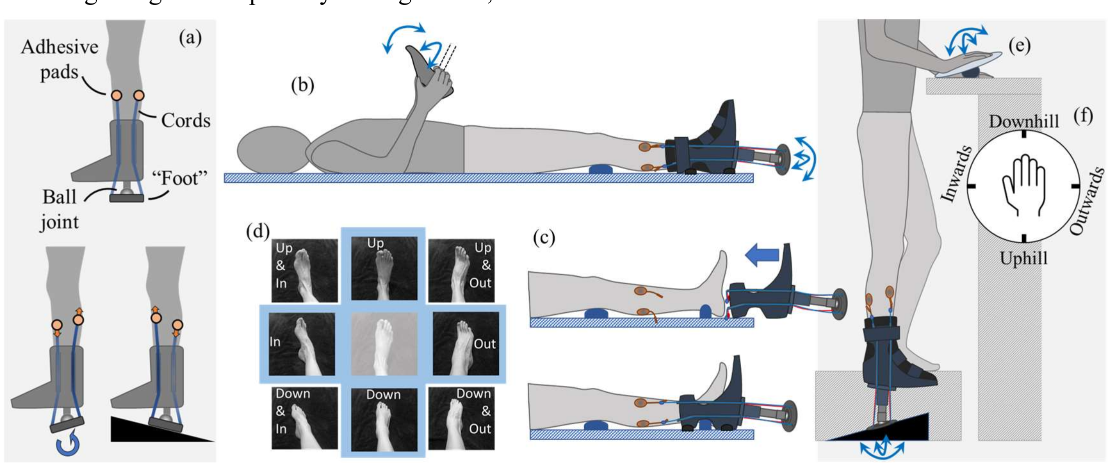

Figure 2. Experimental premise and configuration. (a) Changes in joint posture result in stretching and loosening of soft tissue on opposing sides of the joint. (b) Passive task in primary configuration: with limb-boot contact. Conducted with and without cords connected. (c) Passive task in secondary configuration: no limb-boot contact. The foot was supported in position using foam padding on the underside of the heel. The frame of the boot, with outer padding removed, slid over the foot and ankle so the lateral supports were in line with, but not touching, the sides of the lower limb and the foot was not touching the inner sole. (d) Directions of movement as presented to participants, labelled with descriptors used to verbally refer to posture of foot. (e) Active task. (f) Positions on palm board. Downhill slope (fingers sloping downwards) would correspond to perceived plantarflexion of foot.

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condition and to "focus on the sensation of the boot on the leg" in the *unconnected* condition, during the familiarization procedures. These prompts were not reiterated during the test procedures. Data from the first three participants were excluded from the statistical analysis.

E. Statistical Analysis

Statistical analyses were performed in SPSS v28 (IBM Corp., Armonk, NY, USA). Normality of data was confirmed using Shapiro-Wilk tests and Q-Q plots. Data from Experiments 1a and 1b were analyzed separately but in the same manner. Responses for the three test sets in each condition were tabulated and confusion matrices created. The percentage of correct responses (%Correct), and responses within one adjacent direction (%Adjacent) were recorded, and compared across conditions using two-tailed paired t-tests (*connected*:*unconnected*; alpha at 0.05). Due to experimental error, data from one participant were not collected from the second test set in the *unconnected* condition of Exp. 1a. The corresponding eight trials were removed from the analysis for the *connected* condition, and %Correct and %Adjacent calculated based on adjusted values. Two-tailed one sample t-tests were used to assess whether %Correct and %Adjacent in each condition (*connected*, *unconnected*) were greater than chance occurrence (12.5%, 37.5%, respectively).

For Exp. 2, responses for all 72 trials in each condition were tabulated and confusion matrices created. The percentages of correct responses (%Correct) were compared across conditions (*connected*:*unconnected*) using paired two-tailed t-tests, and one sample t-tests used to assess whether %Correct in each condition was significantly different to chance occurrence (25%). Cohen's d was calculated as a measure of effect size, providing a standardized magnitude of difference in %Correct and %Adjacent for each comparison. Acknowledging a small sample size, the achieved power of the findings for each experiment was calculated using G*Power 3.1.9.7, with an alpha level of 0.05.

III. RESULTS

A. Exp. 1 – Foot orientation perception (Table 1; Fig. 3a,b)

With contact between the lower limb and boot (Fig. 3a), %Correct and %Adjacent were higher in the *connected* in comparison to *unconnected* condition (Fig. 3a). In both *connected* and *unconnected* conditions, %Correct and %Adjacent were greater than chance, with greater effect sizes observed in the *connected* in comparison to the *unconnected* condition. The high number of responses on or close to the descending diagonal of the confusion matrix is clear for the *connected* condition, supporting the statistical results. Evidence of greater values on the primary descending diagonal is also observable in the *unconnected* condition.

Without the limb-boot contact (Fig. 3b), %Correct and %Adjacent were also higher in the *connected* in comparison to the *unconnected* condition. In the *connected* condition, %Correct and %Adjacent were both greater than chance. In the *unconnected* condition, %Correct and %Adjacent were no different from chance, supported by a more random pattern of responses illustrated in the confusion matrix in the *unconnected* condition.

B. Exp. 2 – Perception of slope underfoot (Table 1; Fig. 3c)

In the active lowering task, %Correct was higher in the *connected* in comparison to the *unconnected* condition. In the *connected* condition but not the *unconnected* condition, %Correct was significantly greater than chance occurrence. All participants showed higher accuracy in the *connected* condition and confusion matrices illustrate a more random pattern of responses in the *unconnected* condition.

IV. DISCUSSION

An inability to sense the texture and slope of the ground underfoot could place limitations on an individual's ability to adapt gait for inconsistencies in terrain, contributing to the high fall rates in individuals with amputation [24]. Here, we performed preliminary experiments to explore the efficacy of a mechanical skin stretch array for conveying information about joint posture. We focused on whether movements of an artificial "foot" could be relayed via a configuration of cords, to allow an individual to infer its orientation.

In Exp. 1, with a connection between "foot" and limb participants could consistently infer the orientation of the passively-moved joint to within one direction of the true direction of out eight. Selection of the true direction was less precise but remained significantly greater than chance. Without the connection, the results were substantially poorer; and, in the absence of additional sensory clues (Exp. 1b), not exceeding chance. Effect sizes (*connected*:*unconnected*) remained high without contact between the limb and boot. Acknowledging the minimal training opportunity (~5-min), these findings lend support to the method.

With limb-boot contact (Exp. 1a), a consistently higher-than-chance response in the *unconnected* condition suggests an influence of other sensory inputs. It is likely that participants were able to utilize diffuse pressure sensations from the contact of the boot with the lower leg in making the perceptual judgements of foot orientation. Although the context is not perfectly comparable, this finding illustrates that significant information may be conveyed through the

TABLE I. PASSIVE (EXPERIMENT 1) AND ACTIVE (EXPERIMENT 2) PERCEPTION TESTS.

			Connected[a]					Unconnected[a]					Connected:Unconnected				
Experiment		**Outcome**	$\Delta\%^a$	t^b	*p*	*d*	*Ap*	$\Delta\%^a$	t^b	*p*	*d*	*Ap*	$\Delta\%$	t^b	*p*	*d*	*Ap*
1a	With interface	%Corr	47.2	8.29	<.001	3.13	1	15.6	4.38	.005	1.66	.95	31.6	5.55	.001	2.10	.93
		%Adj	56.5	33.39	<.001	12.62	1	22.6	6.47	.001	2.45	.99	33.9	12.94	<.001	4.89	1
1b	No interface	%Corr	43.7	9.45	<.001	3.57	1	2.2	1.15	.294	0.43	.16	41.5	7.28	<.001	15.08	1
		%Adj	50.0	12.50	<.001	4.72	1	-0.2	-0.08	.940	-0.03	.05	50.2	9.66	<.001	13.75	1
2	With interface	%Corr	31.1	6.30	.003	2.82	.99	1.9	0.58	.591	0.26	.07	29.2	9.49	<.001	4.24	.99

%Corr – percentage of correct responses. %Adj – percentages of responses within one direction of the true direction. Δ% – mean difference in percentage.
[a] comparison with chance occurrence (Exp. 1 = 12.5% or 37.5%, for %Corr and %Adj respectively; Exp. 2 = 25%). [b] two-tailed. Ap = achieved power.

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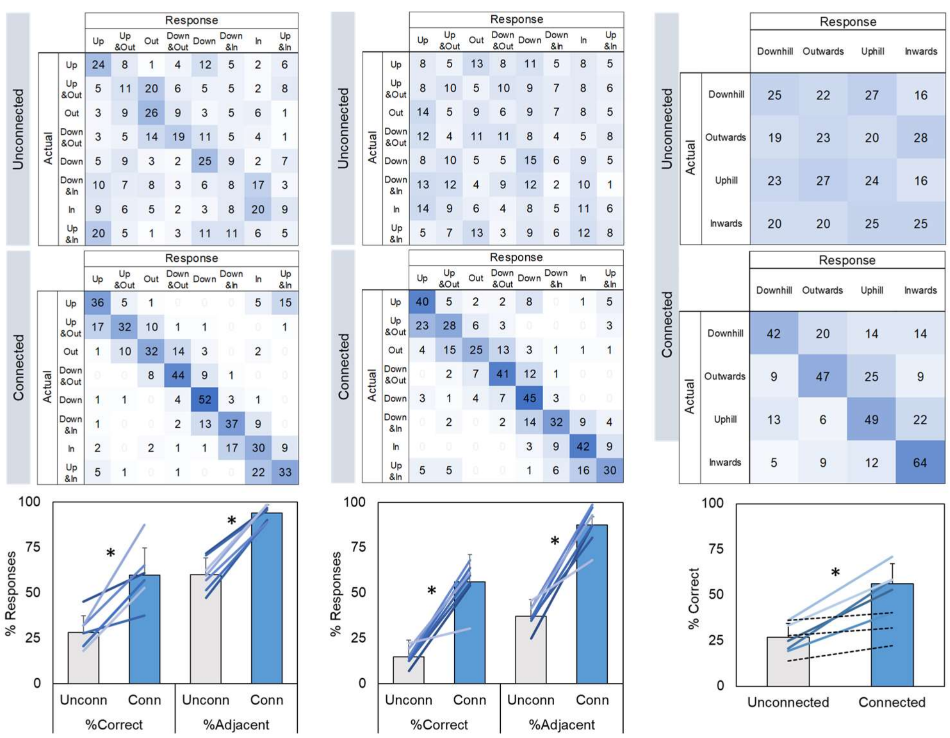
prosthesis via the contact between socket and residual limb. When the leg was isolated from the boot (Exp. 1b), however, correct responses in the *unconnected* condition were no greater than chance, supporting the mechanical connection as the primary source of information for perceptual judgements.

Preliminary testing during an active movement (Exp. 2) yielded a poorer response accuracy, despite the simplification of the task to four directions of movement. The task was more difficult for two reasons. First, the active lowering of the boot (mass 2 kg) to perceive the surface was effortful and novel, and it is possible that the tension on the strings was altered during the maneuver, leading to a weakening of the cues. The addition of tension gauges would assist in evaluating these effects. Second, we provided no direct training on the task itself, nor feedback to participants when performing the perceptual judgements. Despite these challenges, results that were no better than chance without the connection showed significant improvement in the *connected* condition. Although all participants responded positively with the connection, response accuracy was variable across participants. The variability was likely due in part to the individual techniques adopted by each participant; both in making judgments, and physically, in the movement adopted to complete the task. Participants were not given feedback on correctness, so if an individual interpreted the cues inappropriately (e.g., in reverse), they could be wrong uniformly. The familiarization movements conducted prior to testing were intended to expose the participant to the changes in skin sensation that would occur with limb movements causing the "foot" to rotate with respect to the lower leg. Results improved when participants were directed to focus on the sensations at the pads during this movement, suggesting further familiarization that encourages the pairing of sensations with the actions that produce them may result in greater gains. These preliminary results indicate promising intuitiveness, however the repetition of Exp. 2 in individuals who did not complete the first would be required to determine whether it is possible for the technique to be effective with no training.

This study provides proof of concept and presents several areas for further investigation. First, we found the technique to be sensitive to the placement and migration of the adhesive pads. To account for differences in skin sensitivity and elasticity about the circumference of the lower leg, we adjusted cord tension to achieve a similar sensation at each location with similar rotation. Although subjective, this appeared successful, however a more objective method may result in more consistent results. Migration and detachment did occur, and translation of any one pad would have caused tension to be redistributed across the skin. Anecdotally, the effect of this was immediate and noticeable, as participants who had been providing correct responses consistently would begin to make consistent errors. While we reattached or replaced pads that had clearly migrated, and reassessed tension periodically between test blocks, it was likely that tension changes contributed to a lack of accuracy in some cases. In addition to using stronger medical-grade adhesive, a greater number of connections in an array could mitigate this issue in future experiments. We did not test alternative cord configurations or attachment locations, nor the extent to which accuracy of



(a) (b) (c)

Figure 3. Response accuracy in passive (a, b) and active (c) tasks, conducted without (unconn) and with (conn) cords connected to limb. Above: Confusion matrices in unconnected (upper) versus connected (lower) conditions. Values indicate number of responses across all participants. Below: Percentage of correct responses (%Correct) and responses within one direction of the correct direction (%Adjacent; Exp. 1a,b only) across all directions of each task. Lines show individual results. *$p < 0.01$. (a) Exp. 1a: primary configuration (n = 7; 8 directions; max = 62), (b) Exp. 1b: secondary configuration (no limb-boot contact; n=7; 8 directions; max = 63). (c) Exp. 2 (n = 5; max = 90). Black dashed lines: participants 1-3 were provided different instructions during the familiarization procedures (not included in confusion matrices/group mean and standard deviation).

responses is aided by the use of opposing sensations (stretching vs loosening) on opposite sides of the joint.

Although our sample size was small, the high effect sizes and achieved power provide confidence in our results in this young adult sample. Larger scale experiments in a wider range of individuals, including those of the target population are needed to determine whether the technique could be effective for its intended application, and whether further exposure or feedback may be required to achieve similar results.

Finally, this study tested conscious subjective perceptual judgements only, and there was no direct control of the joint to allow perception to be linked to action. Determining whether the technique could lead to more appropriate movement responses during gait or other functional tasks remains an important direction for future enquiry.

V. Conclusion

This study provides preliminary support that proprioceptive information from an artificial joint can be relayed to an individual by means of mechanically-induced skin stretch, configured to mimic the physical effect of biological joint movement on the skin. Due to obvious impracticalities, it is not our intention to promote implementation of this rudimentary equipment (cords, adhesive pads) within an intervention, although it may be viable with refinement of the attachment method. The mechanical connection that delivers a stimulus that is both immediate and relevant, similar to mechanical coupling within the body, is a benefit of this simple technique. Application of low latency stimulation based upon this premise and configuration may be worth future exploration in the development of non-invasive haptic devices for sensory supplementation.

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