Skin Stretch Enhances Illusory Movement in Persons with Lower-Limb Amputation

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Abstract— **Performance of lower limb prostheses is related not only to the mechanical design and the control scheme, but also to the feedback provided to the user. Proprioceptive feedback, which is the sense of position and movement of one's body parts, can improve the utility as well as facilitate the embodiment of the prosthetic device. Recent studies have shown that proprioceptive kinesthetic (movement) sense can be elicited when non-invasively vibrating a muscle tendon proximal to the targeted joint. However, consistency and quality of the elicited sensation depend on several parameters and muscle tendons after lower limb amputation may not always be accessible. In this study, we developed an experimental protocol to quantitatively and qualitatively assess the elicited proprioceptive kinesthetic illusion when non-invasively vibrating a muscle belly. Furthermore, we explored ways to improve consistency and strength of the illusion by integrating another non-invasive feedback method, namely cutaneous information manipulation via skin stretch. Our preliminary results from tests conducted with a person with transtibial (below knee) amputation show that stretching skin while vibrating a muscle belly on the residual limb provided a stronger and more consistent kinesthetic illusion (90%) than only vibrating the muscle (50%). In addition, we found that stretching skin enhances the range (1.5 times) and speed (3.5 times) of the illusory movement triggered by muscle vibration. These findings may enable the development of mechanisms for controlling feedback parameters and for closing the control loop for various walking routines, which may improve performance of lower limb prostheses.**

I. Introduction

Lower limb amputation is a disabling condition that impacts the health and quality of life of affected individuals [1]. Transtibial (below knee) amputations account for most of the major lower limb amputations in the developed world [2]–[4]. Commercially-available ankle–foot prostheses that utilize lightweight passive structures present a promising option for lower limb prosthesis users to provide stability in the stance phase; however, fast walking speeds require the addition of external energy [5]. Recent improvements in battery technology, motor power, and online computer processing have enabled the development of powered devices that operate more naturally and efficiently and are able to adapt to varied walking conditions [6]–[8]. As these devices become more actively involved in walking it will be important to provide the user with information about real-time function. In particular, this information would help users to intuitively plan movements and to make appropriate balance adjustments to prevent falls.

Current standard-of-care lower limb prostheses do not provide users with proprioception, which is the body's spatial sense of position and movement. However, recent advances in approaches for proprioceptive feedback have been shown to significantly improve prosthetic motor control [9]. There are a variety of emergent neural interface technologies that are focused on providing sensory feedback for persons with amputation [10]. However, interfacing directly with the nervous system is largely invasive, requiring surgeries to rewire nerves, to build biological interfaces, or to implant neural and muscular electrode systems [11], [12]. There are clear tradeoffs between complexity, invasiveness, sophistication of signal, and usability. Persons with limb amputation express an interest in advanced technology that is considerably tempered by the realities of prosthesis use and a clear desire for non-invasiveness, simplicity, and ease of use [13].

Kinesthetic feedback based on muscle vibration shows promise as a feedback modality that can be used to provide highly relevant sensory percepts of joint movement while maintaining simplicity. The kinesthetic illusion is a perceptual phenomenon where vibrating a limb muscle at a frequency between 70 and 115 Hz generates a sense of joint movement even though the limb is immobile [14]–[16]. In participants with a surgical neural-machine interface, kinesthetic perception arising from the vibration of the reinnervated muscles improved prosthetic control [9]. However, this type of kinesthetic perceptual feedback does not necessarily require a neural-machine interface. The sense of joint movement could be induced simply by vibrating the native muscles remaining after amputation.

The effective use of the kinesthetic illusion as a reliable feedback method is fundamentally dependent on

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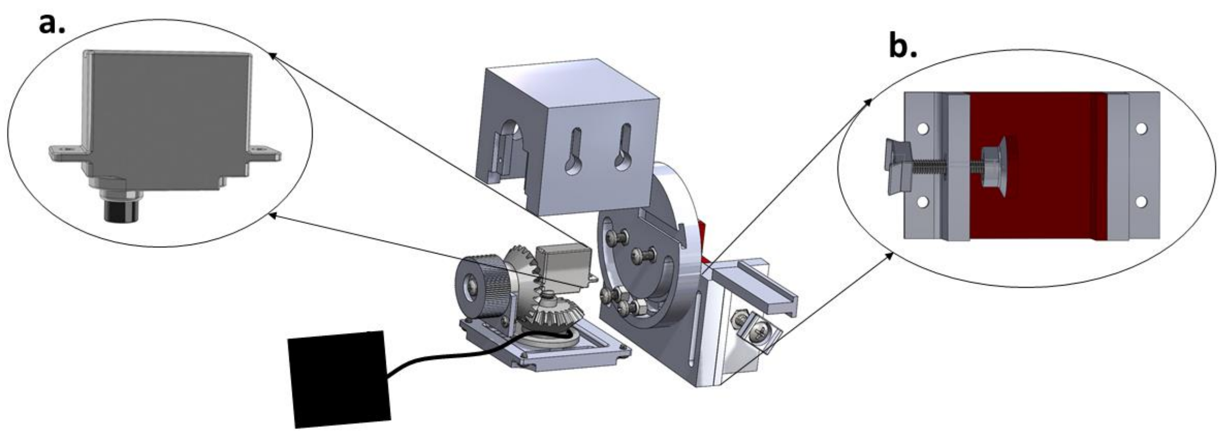

Figure 1. 3D solid model view (exploded) of the skin stretch device. a) Nano servo motor fixed to a bevel gear and a disc used to pull on a thread attached to elastic sports tape. b) 3D printed clamp used to affix the skin stretch device to a chair.

understanding how to introduce vibration such that this phenomenon can be consistently elicited [15]. For instance, consistency and quality of the sensation depend on several parameters [17]. Ferrari et al. investigated the effect of varying some of those parameters, i.e., stimulation point and preload force, on illusory movement sensation [18]. Their results showed that simulating the distal muscle tendon elicited a stronger illusion of movement than stimulating the muscle belly in the upper limbs of able-bodied participants, although amplitude thresholds were similar.

Another method to provide or manipulate proprioceptive feedback may be achieved by manipulating cutaneous information [19]. This method has been shown to influence proprioceptive position sense [20]. Collins et al. investigated the combined effect of vibration and skin stretch on the proprioceptive kinesthetic illusion for lower limb able-bodied participants [21]. They found that vibration applied over the patellar tendon below the knee, along with a skin stretch over the thigh, evoked a higher range of illusory motion compared to only vibration over the patellar tendon. However, for persons with limb amputation, tendons may not always be accessible and, hence, it may become challenging to elicit a strong illusion of movement.

For lower limb prostheses applications, it is important to not only investigate the possibility of eliciting the kinesthetic illusion, but to also explore ways to improve consistency and strength of the illusion by integrating other non-invasive feedback methods, namely cutaneous information manipulation via skin stretch. In this preliminary study, we developed an experimental protocol to quantitatively and qualitatively assess the elicited kinesthetic illusion. We used this protocol to assess the elicited kinesthetic illusion from two stimulation conditions (muscle vibration and combined muscle vibration with skin stretch) on a participant with transtibial amputation. Our preliminary results show that stretching skin while vibrating a muscle belly on the residual limb provided a stronger kinesthetic illusion than only vibrating the muscle. In addition, we found that stretching skin may enhance the range and speed of the illusory movement triggered by muscle vibration.

II. MATERIALS AND METHODS

A. *Device Development*

In order to have a reliable and consistent method for pulling skin on the residual limb of a person with lower limb amputation, we developed a device using an ultra-nano servo motor HS35HD (Hitec RCD, USA) attached to elastic sports Kinesio Tape (Kinesio Holding Corp., USA) via a thread. This motor was selected for its small size (18.6 x 7.6 x 15.5 mm), light weight (4.5 g) and high torque (0.8 N cm) (Figure 1a). We designed a three-dimensional (3D) printed enclosure for this motor to facilitate its handling and fixation on a prosthesis or a chair without entangling the attached thread or compromising the device's performance (Figure 1).

In this study, the skin stretch device was mounted to a chair using a 3D-printed device specific-clamp (Figure 1b). This clamp facilitated position adjustment and rotation of the skin stretch device to accommodate for different testing procedures.

Similar to other studies [9], a commercial handheld variable vibration unit Vibrasens VB200 (Techno Concept, Mane, France) was used to elicit movement sensation by vibrating proximal muscle tendon and muscle belly at the residual limb. The device vibration was set at 90 Hz with a fixed neutral-to-peak amplitude of 0.5 mm [15].

B. *Participant Information*

A 58 year old male with a right transtibial amputation volunteered to participate in this study. Written informed consent according to the University of Alberta Research Ethics Board (HREB Pro00063695) was obtained from the participant.

C. *Experimental Protocol*

After obtaining consent from the participant, he was asked to remove his prosthesis and sit comfortably on a high chair, therefore allowing his lower limb muscles to relax (Figure 2).

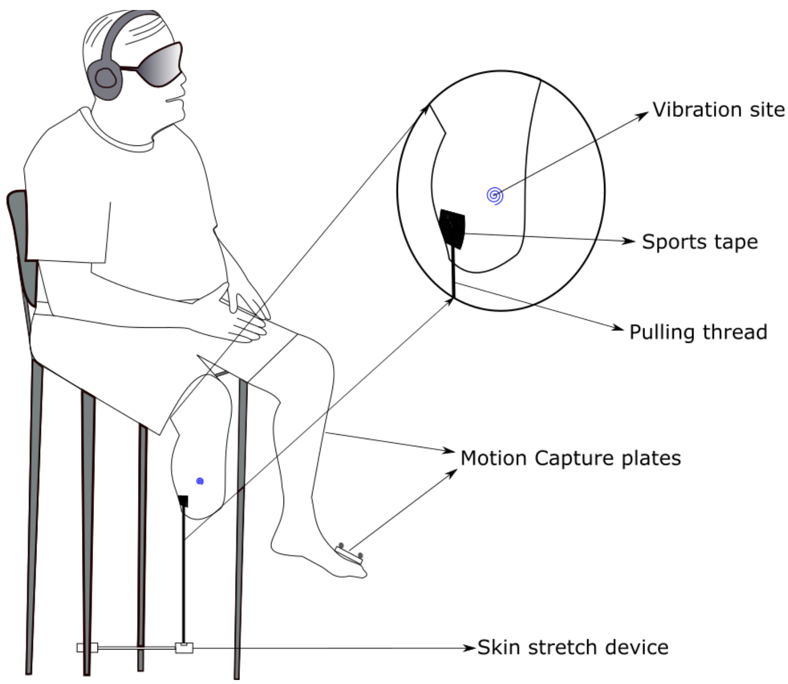

Figure 2. Experimental setup. Participant sitting comfortably on a high chair during a vibration and skin stretch trial.

The participant was introduced to the first phase of the experiment, which was perceptual mapping using the vibration device, but was not informed about the intent of the study. To ensure that both audio and visual cues were occluded [22], the participant wore a blindfold and a noise cancelling headset playing Brownian noise. The vibration device was pressed into the muscle bellies of the gastrocnemius lateral, tibialis anterior, and fibularis longus muscles on his residual limb with a preload force of 2 to 2.5 N [16] and activated for 15 seconds. At least three sites were vibrated along each muscle and the participant was asked to report any sensation beyond simple vibration. If an illusory movement sensation was perceived, the vibrated site was marked for further investigation. After all sites were explored, motion capture plates [23] were attached to the participant's intact limb.

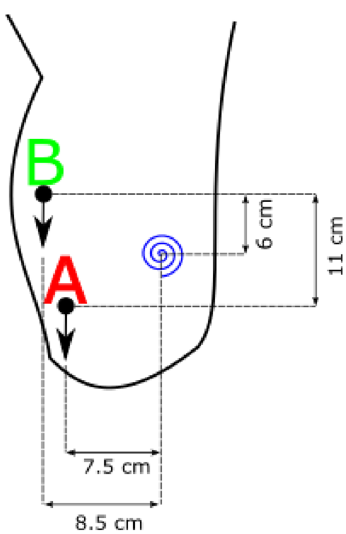

Figure 3. Investigated skin stretch sites on the residual limb. Site A or B was pulled downwards while vibrating the muscle at the spot indicated by a blue spiral.

During the second phase of this experiment, the marked site with the strongest illusory movement sensation was vibrated, and the participant was asked to demonstrate what he felt in configuration, velocity and duration with his intact limb simultaneously [24]. This procedure was repeated 10 times and the movement of his intact limb was recorded using an optical motion capture system (Optitrack, NaturalPoint., Inc, Oregon, USA). Subsequently, the participant was asked to rate the realism of the illusory movement on a scale from 1 to 5 (with 1 being a weak movement illusion and 5 being a strong movement illusion). A mandatory 5-minute rest break was scheduled between each of the testing conditions. We investigated three testing conditions in the following order: vibration + skin stretch at site A, vibration only, and vibration + skin stretch at site B (Figure 3). Only for the skin stretch testing conditions, elastic sports tape was placed on the participant's residual limb. This tape was pulled downwards using the developed skin stretch device, whose operation was synchronized with the vibration device. Figure 3 shows the sites to which the sports tape was attached. These sites were selected to align with the direction of the physiological skin stretch occurring during foot dorsiflexion.

D. Outcome Measures

The following outcome measures were used to investigate the effectiveness of skin stretch in enhancing the vibration-induced kinesthetic illusion.

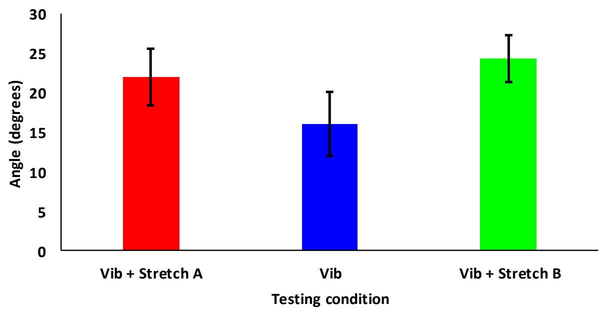

Figure 4. Average final dorsiflexion angle reached for each testing condition.

a) **Dorsiflexion Angle**: the angle between the resting foot position relative to the lower leg (of the intact indicator limb) at the start of a trial and the final foot position at the end of this trial. Larger angles correspond to larger range of movement.

b) **Strength of Illusion**: a categorical measure of the perceived movement sensation reported by the participant after each trial. This measure is reported on a scale from 1 to 5, where 1 corresponds to a very weak movement illusion and 5 corresponds to a strongly perceived movement sensation.

c) **Illusory Movement Trajectory:** the average movement profile recorded by the motion capture system of the intact limb matching the perceived illusory movement of the missing limb.

d) **Feedback Reliability (FR)**: the ratio between trials with perceived movement and the total number of trials per testing condition (Equation 1). The higher the ratio, the more reliable and consistent the feedback.

$$FR = \frac{N_m}{N} \quad (1)$$

where N_m is the number of trials with perceived kinesthetic illusion and N is the total number of trials.

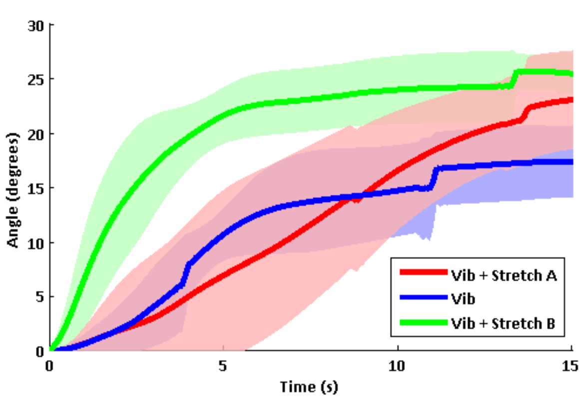

Figure 5. Perceived foot dorsiflexion illusory movement of the missing limb recorded by matching sensation using the intact limb for each testing condition.

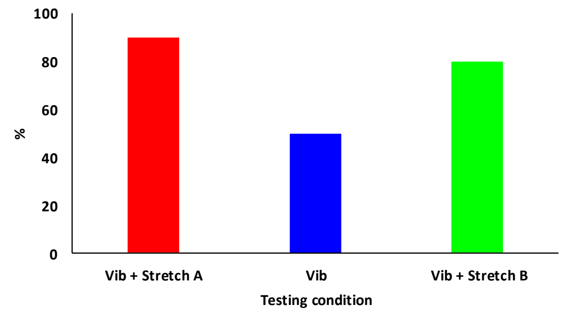

Figure 6. Feedback reliability assessed for each testing condition. Adding skin stretch to the vibration of the residual muscle increased the consistency of the kinesthetic illusion.

III. Results

We investigated stretching skin at two sites on the residual limb as a method to enhance the kinesthetic illusion initiated by vibrating a muscle in that residual limb. For each site, 10 trials of a movement-matching task were initiated. Trials that elicited a movement sensation were recorded using a motion capture system; the averaged results and standard deviations are presented.

a) Dorsiflexion Angle

Vibration accompanied by skin stretch at sites A and B resulted in higher dorsiflexion angles ($22 \pm 3.6^\circ$ and $24 \pm 3.0^\circ$, respectively) than vibration alone ($16 \pm 4.0^\circ$) (Figure 4). These results suggest that a pull downwards on the skin may enhance the range of perceived movement illusion of the missing limb.

b) Strength of Illusion

The average reported strength of movement illusion was similar across all testing conditions (Vib + Stretch A = 3.8 ± 0.6, Vib = 3.7 ± 0.5, and Vib + Stretch B = 3.8 ± 0.3).

c) Illusory Movement Trajectory

Kinematic results (Figure 5) show that stretching the skin at a proximal site (site B) induced a faster illusory movement than stretching skin at the distal site (site A). Although both "vibration only" and "vibration + skin stretch A" conditions had a similar starting illusory movement speed, the "vibration + skin stretch A" condition enabled an almost constant illusory movement speed throughout the trial duration. Comparing the speed of illusory movement evoked by each condition during the first 5 seconds, Figure 5 shows that the "vibration + skin stretch B" condition elicited an average illusory movement range that is 2 times higher than the "vibration" condition and almost 3.5 times higher than the "vibration + skin stretch A" condition.

d) Feedback Reliability

The consistency of the illusion sheds light on the reliability of the feedback. In this study, the participant reported perceiving movement sensation of his missing limb for 50% of the vibration only trials. Interestingly, this percentage was increased when skin stretch was added to the vibration (site A = 90% and site B = 80%) (Figure 6).

IV. Discussion

Many studies have focused on improving performance of lower limb prostheses by exploring various mechanical and control designs [7], [25], passive and active joints [6], and invasive and non-invasive feedback [26], [27]. Control signal noise and high latency, along with the lack of proprioceptive feedback, present a challenge for improving lower limb prosthesis performance [28]. Restoring proprioceptive kinesthetic feedback has recently been found to improve performance of upper limb prosthesis users [9]. Intrigued by this finding, we explored methods to elicit a strong proprioceptive kinesthetic illusion in a person with lower limb amputation, with the goal of improving lower limb prosthesis performance by closing the control loop and restoring this lost feedback.

To elicit a reliable and consistent kinesthetic illusion, we explored vibrating muscles on the residual limb of a participant with a transtibial amputation and combining this vibration with skin stretch. Our results showed that only vibrating the gastrocnemius muscle belly elicited an inconsistent ankle illusory movement sensation. As expected, when combining this vibration of the muscle with stretching the skin at the residual limb, the consistency of the illusory movement sensation was improved by an additional 30% to 40%, depending on the stretch site.

Prior to investigating the effect of combining skin stretch with muscle vibration, we conducted a pilot study with 3 able-bodied participants following the same experimental protocol presented here to determine the most effective skin stretch sites that best match with the physiological movement of the ankle. In that pilot study, we placed one piece of sports tape at a time along the tibialis anterior and gastrocnemius muscles. This piece of tape was pulled down while vibrating muscle tendons, simulating foot dorsiflexion. However, many of the skin stretch sites that were determined for able-bodied participants were either missing or overlapping with the vibration site on the residual limb of the participant in this study. In addition, the length of the residual limb and the skin sensitivity around the amputation area presented a challenge when determining the most effective vibration site that would invoke the kinesthetic illusion.

Both of the investigated skin stretch sites augmented the range of the kinesthetic illusion of foot dorsiflexion. Unexpectedly, the skin stretch site closer to the end of the residual limb, i.e., closer to the phantom ankle (site A), did not enable the largest range of illusory movement; however, the illusory movement induced by stretching this site did not seem to reach a plateau after 10 seconds of vibration. We suspect that there was an unexplored interplay between the vibration and this skin stretch site since they were in close proximity to each other. In addition, we suspect that the skin at this site was stretched in an undesired direction because of the preload force applied at the vibration site.

For any real-time application, the ability to vary the information relayed in a feedback loop becomes crucial. For instance, we found that stretching skin more proximally (site B) on the residual limb increased the speed of illusory movement while stretching the skin distally evoked a slower movement illusion. Combined, these two findings suggest further work may elucidate mechanisms for controlling feedback parameters in closing the control loop for varying speeds of walking.

This study provides a protocol for testing and assessing the kinesthetic illusion for persons with lower limb amputations. This protocol will be used to investigate the generalizability of our preliminary results presented here by collecting data from persons with lower limb amputations at different levels.

Future work enabled by this study includes investigation of the feasibility of using proprioceptive kinesthetic feedback to enhance the embodiment of lower limb prosthetic devices, improving control for balance adjustment using a triggering device [29], and investigating the effectiveness of this feedback for walking and balance correction.

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References

[1] P. Kvaliteta, Ž. Pacijenata, N. Amputacije, and D. Ekstremiteta, "Assessment of Quality of Life in Patients After Lower Limb Amputation," *Med. Pregl.*, vol. 68, no. 3–4, pp. 103–108, 2015.

[2] T. R. Dillingham, L. E. Pezzin, and E. J. MacKenzie, "Limb Amputation and Limb Deficiency: Epidemiology and Recent Trends in The United States," *South. Med. J.*, vol. 95, no. 8, pp. 875–883, 2002.

[3] S. Y. Chen, W. C. Chie, C. Lan, M. C. Lin, J. S. Lai, and I. N. Lien, "Rates and characteristics of lower limb amputations in Taiwan , 1997," *Prosthet. Orthot. Int.*, vol. 26, pp. 7–14, 2002.

[4] M. P. Dillon, F. Kohler, and V. Peeva, "Incidence of Lower Limb Amputation in Australian Hospitals From 2000 To 2010," *Int. Soc. Prosthetics Orthot.*, vol. 38, no. 2, pp. 122–132, 2014.

[5] A. H. Hansen, D. S. Childress, S. C. Miff, S. A. Gard, and K. P. Mesplay, "The Human Ankle During Walking: Implications for Design of Biomimetic Ankle Prostheses," *J. Biomech.*, vol. 37, no. 10, pp. 1467–1474, 2004.

[6] E. J. Rouse, N. C. Villagaray-carski, R. W. Emerson, and H. M. Herr, "Design and Testing of a Bionic Dancing Prosthesis," *PLoS One*, vol. 10, no. 8, 2015.

[7] H. M. Herr and A. M. Grabowski, "Bionic Ankle – Foot Prosthesis Normalizes Walking Gait for Persons with Leg Amputation," *Proc. R. Soc.*, vol. 279, pp. 457–464, 2012.

[8] M. F. Eilenberg, H. Geyer, and H. Herr, "Control of a Powered Ankle-Foot Prosthesis Based on a Neuromuscular Model," *Ieee Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no. 2, pp. 164–173, 2010.

[9] P. D. Marasco *et al.*, "Illusory movement perception improves motor control for prosthetic hands," *Sci. Transl. Med.*, vol. 10, no. 432, 2018.

[10] J. S. Schofield, K. R. Evans, J. P. Carey, and J. S. Hebert, "Applications of sensory feedback in motorized upper extremity prosthesis: a review," *Expert Rev Med Devices*, vol. 11, no. 5, pp.

499–511, 2014.

[11] J. S. Hebert *et al.*, “Novel Targeted Sensory Reinnervation Technique to Restore Functional Hand Sensation After Transhumeral Amputation,” *IEEE Trans. neural Syst. Rehabil. Eng.*, vol. 22, no. 4, pp. 765–773, 2014.

[12] S. Raspopovic *et al.*, “Restoring natural sensory feedback in real-time bidirectional hand prostheses.,” *Sci. Transl. Med.*, vol. 6, no. 222, pp. 1–10, 2014.

[13] S. M. Engdahl, B. P. Christie, B. Kelly, A. Davis, C. A. Chestek, and D. H. Gates, “Surveying the interest of individuals with upper limb loss in novel prosthetic control techniques,” *J. Neuroeng. Rehabil.*, pp. 1–11, 2015.

[14] G. M. Goodwin, D. I. Mccloskey, and P. B. C. Matthews, “The contribution of muscle afferents to keslesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents,” *Brain*, vol. 95, pp. 705–748, 1972.

[15] J. S. Schofield, M. R. Dawson, J. P. Carey, and J. S. Hebert, “Characterizing the effects of amplitude, frequency and limb position on vibration induced movement illusions: Implications in sensory-motor rehabilitation,” *Technol. Heal. Care*, vol. 23, pp. 129–141, 2015.

[16] E. Tidoni, G. Fusco, D. Leonardis, A. Frisoli, M. Bergamasco, and S. Maria, “Illusory movements induced by tendon vibration in right- and left-handed people,” *Exp. Brain Res.*, vol. 233, pp. 375–383, 2015.

[17] M. W. Taylor, J. L. Taylor, and T. Seizova-cajic, “Muscle Vibration-Induced Illusions : Review of Contributing Factors , Taxonomy of Illusions and User ’ s Guide,” *Multisens. Res.*, vol. 30, pp. 25–63, 2017.

[18] F. Ferrari, F. Clemente, and C. Cipriani, “The preload force affects the perception threshold of muscle vibration- induced movement illusions,” *Exp. Brain Res.*, 2018.

[19] B. B. Edin, “Cutaneous afferents provide information about knee joint movements in humans,” *J. Physiol.*, vol. 531, no. 1, pp. 289–297, 2001.

[20] I. A. Kuling, E. Brenner, and J. B. J. Smeets, “Proprioceptive Localization of the Hand Changes When Skin Stretch around the Elbow Is Manipulated,” vol. 7, 2016.

[21] D. F. Collins, K. M. Refshauge, G. Todd, and S. C. Gandevia, “Cutaneous Receptors Contribute to Kinesthesia at the Index Finger , Elbow , and Knee,” *J. Neurophysiol.*, vol. 94, pp. 1699–1706, 2005.

[22] M. Guerraz, S. Provost, R. Narison, A. Brugnon, S. Virolle, and J. Bresciani, “Integration of Visual and Proprioceptive Afferents in Kinesthesia,” *Neuroscience*, vol. 223, pp. 258–268, 2012.

[23] Q. A. Boser *et al.*, “Cluster-based upper body marker models for three-dimensional kinematic analysis : Comparison with an anatomical model and reliability analysis,” *J. Biomech.*, vol. 72, pp. 228–234, 2018.

[24] S. Hillier, M. Immink, and D. Thewlis, “Assessing Proprioception : A Systematic Review of Possibilities,” *Neurorehabil. Neural Repair*, vol. 29, no. 10, pp. 933–949, 2015.

[25] C. D. Hoover, G. D. Fulk, and K. B. Fite, “The Design and Initial Experimental Validation of an Active Myoelectric Transfemoral Prosthesis,” *J. Med. Device.*, vol. 6, 2019.

[26] F. W. Clippinger, J. H. Mcelhaney, M. G. Maxwell, D. W. Vaughn, G. Horton, and L. Bright, “Prosthetic Sensory Feedback Lower Extremity,” *Prosthetics Orthot. Clin.*, vol. 5, no. 3, 1981.

[27] R. E. Fan *et al.*, “A Haptic Feedback System for Lower-Limb Prostheses,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 3, pp. 270–277, 2008.

[28] M. Windrich, M. Grimmer, O. Christ, S. Rinderknecht, and P. Beckerle, “Active lower limb prosthetics : a systematic review of design issues and solutions,” *Biomed. Eng. Online*, vol. 15, no. 3, pp. 5–19, 2016.

[29] M. Keri, A. W. Shehata, Q. A. Boser, A. H. Vette, and J. S. Hebert, “Development and Verification of a Low-Cost Prosthetic Knee Motion Sensor,” *IEEE Life Sci. Conf.*, pp. 283–286, 2018.