Prosthesis embodiment and attenuation of prosthetic touch in upper limb amputees – a proof-of-concept study

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28 **Highlights**

- 29 • Immediate and prosthetic self-touch is attenuated compared to external touch.
- 30 • Immediate and prosthetic self-touch do not differ in intensity.
- 31 • Prosthesis embodiment predicts attenuation of prosthetic self-touch.
- 32 • Results suggest that embodied prostheses can be represented as actual limbs.

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Abstract

The phenomenon of sensory attenuation, that is, the perceptual reduction of intensity for self-generated stimuli, is considered a neurocognitive basis for self-other distinction. Corroboratory, such perceptual attenuation has been shown to be dependent on the sense of embodiment, that is, the perceptual incorporation of an object or body part into one's body representation. In the present study, we tested whether this relationship is transferrable to unilateral upper limb amputees using a prosthesis. Thirteen participants were asked to touch their foot sole with a) their intact hand (self-touch), b) their prosthesis (prosthesis-touch), or c) let it be touched by another person (other-touch). Intensity of touch was assessed with a questionnaire. In addition, prosthesis embodiment was assessed by the recently introduced Prosthesis Embodiment Scale in nine participants. We found that both self-touch as well as prosthesis-touch was characterized by significant perceptual attenuation compared to other-touch, while self- and prosthesis-touch did not differ. By calculating an index reflecting how similar prosthesis-touch was to self- or other touch and correlating this index with perceived prosthesis embodiment, we found that the more embodied the prosthesis was, the more similar was its elicited touch perception to actual self-touch. This association was specific for prosthesis embodiment, since neither prosthesis satisfaction nor prosthesis adjustment showed a similar relationship. These findings are further evidence that perceptually embodied prostheses can be represented as an actual limb by the users' sensorimotor system, which might have important implications for future prosthetic rehabilitation.

Keywords: Embodiment; Forward model; Prosthesis; Self-touch; Sensory attenuation

1 Introduction

If you have ever tried to tickle yourself, you probably failed: while another person's touches on sensitive body areas are perceived as intense and ticklish, self-touch is experienced as faint in comparison. The question as to why people are usually unable to tickle themselves has fascinated for centuries (Harris, 1999), since the answer could give insight into one of the most existential issues: what is the core of self-perception?

It has been early proposed that the inability to tickle oneself might be the consequence of an active attenuation of self-produced stimulation. Computational motor control theories (e.g., Bays & Wolpert, 2008) focused on the potential underlying mechanisms. These forward models propose that self-generated movements produce a representational replica in the brain, the so-called efference copy (Wolpert & Flanagan, 2001; Wolpert & Ghahramani, 2000), which is used to predict the movement's sensory consequences. If the prediction is met, touch-associated neural activation would be cancelled in a top-down manner, with analogue perceptual effects.

In line with the forward models, it has been experimentally shown that the processes underlying the attenuation of self-touch are predictive, not postdictive (Bays, Flanagan, & Wolpert, 2006), and can be best explained by the involvement of an efference copy for self-generated movements (Kilteni, Engeler, & Ehrsson, 2020). Other empirical data revealed the importance of spatio-temporal synchrony between motor and sensory signals (Blakemore, Frith, & Wolpert, 1999) and of the alignment of touch-receiving and touch-producing body parts (Kilteni & Ehrsson, 2017b) for the perceptual attenuation of self-touch. Moreover, self-touch appears to be predicted based on the anticipated position of the effector, which does not necessarily have to be an actual body part: one's own hands as well as tools attached to the body elicit comparable attenuation of touch if there is direct and aligned physical contact with another body area (Kilteni & Ehrsson, 2017b). Finally, neurophysiological studies using advanced experimental setups for the transmission of external or self-generated tactile stimuli indicated that the cerebellum is involved in the comparison of predicted and actual sensory input as a consequence of one's own actions (Blakemore, Frith, & Wolpert, 2001;

Blakemore, Wolpert, & Frith, 1998; Shergill et al., 2013), whose reduced activity functionally co-varies with responses of the somatosensory system (Blakemore, Wolpert, & Frith, 1999) and the perceptual attenuation of self-touch (Kilteni & Ehrsson, 2020). Taken together, these results support the validity of computational forward models for explaining the neural and perceptual effects associated with self-touch, and suggest that the underlying mechanisms constitute a basic system for the distinction between self and non-self.

The efference copy, however, is only one mechanism the representation of the self can rely on. The detection and integration of coherent multiple exteroceptive or interoceptive modalities has also been argued to be crucial for self-other distinction and in the formation of the bodily self (Park & Blanke, 2019; Suzuki, Garfinkel, Critchley, & Seth, 2013; van Elk, Lenggenhager, Heydrich, & Blanke, 2014). By the application of synchronous visuo-tactile stimulation on a visible rubber hand and the participant's occluded hand, Botvinick and Cohen (1998) famously showed that healthy participants perceive a rubber hand as being their own hand. Subsequent studies, using this so-called rubber hand illusion (RHI) or its derivatives, revealed the universality of the underlying processes (see for a review Riemer, Trojan, Beauchamp, & Fuchs, 2019), which primarily base on the temporal and spatial correlation of multisensory or sensorimotor input. The perceptual incorporation of the rubber hand into one's body representation, that is, embodiment of the artificial limb (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008), has previously been related to behavioral (Botvinick & Cohen, 1998; Longo et al., 2008), peripheral physiological (Armel & Ramachandran, 2003; Moseley et al., 2008), and central neurophysiological measures (Ehrsson, Holmes, & Passingham, 2005; Ehrsson, Spence, & Passingham, 2004). Embodiment has further been assumed to represent a basic neurobiological mechanism for the discrimination between oneself and others (e.g., Ehrsson, 2020), and its pivotal nature is emphasized by corresponding behavioral evidence even for non-primate mammals (Wada, Takano, Ora, Ide, & Kansaku, 2016).

Although the multimodal integration mechanisms underlying perceptual embodiment are subject of scientific investigations for more than 20 years, till recently, it remained open

how they would contribute to the perceptual attenuation of self-touch. In order to close this critical gap of knowledge, Kilteni and Ehrsson (2017a) combined the RHI paradigm with a behavioral force-matching task: participants received a touch with varying forces via a stimulator attached to their left index finger and were subsequently asked to reproduce this force with their right index finger by pressing a force sensor. The force was then transmitted again to the left index finger. Previous studies found systematical reductions in force reproduction (Bays & Wolpert, 2008; Shergill, Bays, Frith, & Wolpert, 2003; Shergill, Samson, Bays, Frith, & Wolpert, 2005) which have been related to the perceptual attenuation of self-touch. In Kilteni and Ehrsson's (2017a) study, the relative position of sensor and stimulator in the horizontal plane could be varied in a way that allowed for placing both hands either 25 cm apart or one above the other. Using this setup, the authors showed that reduced attenuation of self-touch, caused by misalignment between both hands, can be compensated if the left hand is touched by an aligned and embodied rubber hand: the more the rubber hand was embodied, the stronger the perceptual attenuation effect. In a second experiment, the authors further showed that the more the rubber hand was embodied, the lesser the attenuation effect for self-touch applied with the actual, but disembodied, right index finger. These results suggest that perceptual embodiment updates internal body representations underlying the sensory predictions of the forward model. By eliminating efferent signals from the RHI paradigm, the contributing role of embodiment to perceptual attenuation of self-touch has been re-produced (Burin, Pyasik, Salatino, & Pia, 2017) and related to similar neurophysiological mechanisms compared to actual self-touch (Pyasik et al., 2019).

Although the RHI has been widely used for the investigation of embodiment experiences in normally-limbed participants, it has been suggested to also be relevant for clinical applications (Niedernhuber, Barone, & Lenggenhager, 2018). Limb amputations, for instance, represent a serious breach of one's physical integrity, and prostheses are used to restore it. The RHI has been used as an experimental model also for the embodiment of prostheses: as Ehrsson et al. (2008) showed, even upper limb amputees perceive the RHI when the occluded residual limb is tactilely stimulated in synchrony with an observed artificial

limb. Accordingly, Murray (2004) reported that amputees differ in their level of perceptual prosthesis embodiment, with some of them perceiving the device as integral part of their body, while others experience it as mere tool. Prosthesis embodiment has also been associated with beneficial effects for the amputee's body posture (Imaizumi, Asai, & Koyama, 2016) and with reduced levels of phantom limb pain (Bekrater-Bodmann et al., in press). Recently, it has been shown that perceptual prosthesis embodiment in lower limb amputees is common and displays qualitative similarity (Bekrater-Bodmann, in press) to embodiment experiences induced in normally-limbed controls using the RHI (Longo et al., 2008).

To our knowledge, the phenomenon of perceptual attenuation of self-touch has never been investigated for prosthesis use. However, based on the theoretical and empirical considerations described above, one can assume that prosthesis-touch might have comparable effects than actual self-touch, especially if perceptually embodied: a) touch applied by tools induces perceptual attenuation and corresponding neurophysiological effects which are comparable to actual self-touch (Kilteni & Ehrsson, 2017b; Pazen et al., 2020), b) humans can rapidly adapt to altered conditions of sensory prediction (Kilteni, Houborg, & Ehrsson, 2019), and c) embodiment, which can be commonly achieved in limb amputees (Bekrater-Bodmann, in press), contributes to the perceptual attenuation of self-touch (Burin et al., 2017; Kilteni & Ehrsson, 2017a). Evidence for perceptual attenuation of prosthesis touch would be relevant not only for basic research on body representation, but would further support preliminary findings showing that the artificial limb can neurocognitively become part of the user (Maimon-Mor & Makin, 2020; van den Heiligenberg et al., 2018), which in turn might have important clinical implications.

Thus, in the present study, we compared the perceptual consequences of self-touch (i.e., touching oneself with the intact hand), prosthesis-touch (i.e., touching oneself with the prosthesis), and other-touch (i.e., touch applied by another person) in a sample of unilateral upper limb amputees regularly using a prosthesis. We hypothesized that there is perceptual attenuation in both self-touch and prosthesis-touch compared to other-touch, while self-touch and prosthesis-touch should not significantly differ. In order to test the role of prosthesis

embodiment, we assessed perceptual incorporation of the device and correlated this measure with perceptual attenuation of self-touch. We predicted prosthesis-touch to be more similar to self-touch in individuals with high prosthesis embodiment.

2 Methods

2.1 Participants

In total, 13 upper limb amputees using a prosthesis were included, composed of participants previously included in other studies conducted at the Central Institute of Mental Health, mainly recruited from the PHANTOMMIND cohort (initial sample description by (Bekrater-Bodmann et al., 2015). The sample's age ranged from 40 to 75 years (mean (M) = 60.31; standard deviation (SD) = 8.75). Twelve participants were males, and all participants were right handers prior to amputation. The amputation dated back $M = 29.54$ years ($SD = 17.79$). The length of the residual limb, measured from the caput humeri, ranged from 0% to 90% ($M = 47.00$ %; $SD = 33.82$). Six participants reported using a cosmetic prosthesis and seven participants used a myoelectric device. Individual demographic and clinical information of participants is given in Table 1. Prior to participation, participants provided their written informed consent. The study was approved by the Ethics Committee II of Heidelberg University, and is in accordance with the Declaration of Helsinki in its current version.

214 Table 1: Demographic and clinical details of the participants.

participant #	sex	age (years)	time since amputation (years)	side of amputation	reason of amputation	residual limb length (%) ^a	Phantom limb awareness ^b	prosthesis type	prosthesis use per week	prosthesis use per day
1	m	61	22	R	accident	30	no	myoelectric	daily	all day
2	m	56	3	R	accident	10	yes	myoelectric	every 2nd day	all day
3	m	56	36	L	accident	20	yes	cosmetic	daily	all day
4	m	57	32	R	accident	60	no	myoelectric	daily	all day
5	f	64	9	L	accident	85	yes	cosmetic	almost daily	all day
6	m	60	18	R	accident	0	yes	myoelectric	daily	all day
7	m	75	67	R	accident	75	yes	cosmetic	daily	several hours
8	m	68	43	R	accident	85	yes	cosmetic	daily	all day

9	m	40	27	R	accident	50	no	myoelectric	less than twice	1-2 hours
10	m	68	48	R	PVD	90	no	cosmetic	daily	all day
11	m	68	44	L	accident	80	yes	myoelectric	daily	all day
12	m	54	16	L	accident	15	yes	myoelectric	less than twice	several hours
13	m	57	19	L	accident	10	yes	cosmetic	less than twice	1-2 hours

215 ^a measured from caput humeri; ^b in the last four weeks; m = male; f = female; L = left, R = right; PVD = peripheral vascular disease; bold font

216 indicates data collection by questionnaire.

2.2 Setting

Data of four participants (#1-4, Table 1) were gathered in the context of a postally sent survey. Participants were instructed by written to accomplish the experiment (fixed order of conditions). Nine additional participants (#5-13, Table 1) were contacted via telephone and were verbally guided through the experiment (randomized order of conditions). All participants were asked to have a supportive person present when the experiment was conducted.

2.3 Procedure

2.3.1 Demographic and clinical data

Age, sex, as well as year, side, and reason of amputation, handedness prior to amputation, residual limb length, and presence of phantom limb awareness (in the last four weeks) was acquired from all participants. Participants were further asked for the type of prosthesis and frequency of its use (per day and week). Demographic and clinical data are provided in Table 1.

2.3.2 Other measures

The nine amputees participating in the telephone experiment also completed two instruments targeting prosthesis experiences.

The *Prosthesis Embodiment Scale* (Bekrater-Bodmann, in press), adapted for use in upper limb amputees (i.e., PEmbS-ULA; see supplement for German and English versions) was conducted in an interview fashion. The PEmbS-ULA consists of ten items targeting experiences of ownership, perceived physical integrity, agency, and anatomical plausibility related to the prosthetic device. Participants were asked to watch at or move the prosthesis (opening/closing the hand for myoelectric prostheses; lifting/lowering for cosmetic prostheses), before indicating their agreement or disagreement with given statements (for example ‘The prosthesis is part of my body.’) using a Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree). In lower limb amputees, the PEmbS has previously been

shown to have good to excellent reliability, and positive associations to locomotor capability, prosthesis satisfaction, and prosthesis adjustment suggest validity of the instrument (Bekrater-Bodmann, in press). For the present study, the PEmbS-ULA total scale score was used, ranging from -3 to +3, with higher scores indicating higher prosthesis embodiment.

The *Trinity Amputation and Prosthesis Experience Scales – Revised* (TAPES-R; (Gallagher, Franchignoni, Giordano, & MacLachlan, 2010) is a widely used instrument developed to multidimensionally assess adaptation to and evaluation of the prosthetic device and prosthesis use in limb amputees. The reliability and validity of the upper limb adaption has been demonstrated before (Desmond & MacLachlan, 2005). For the present study, a German translation of the TAPES-R, adapted for upper limb amputees, was used (provided by the Centre for Orthopaedic and Trauma Surgery, Heidelberg University Hospital, Heidelberg, Germany). The TAPES-R was implemented in an interview fashion. The *Aesthetic* (three items) and *Functional Satisfaction* (five items) subscales of the *Satisfaction with Prosthesis* scale were used to assessed prosthesis satisfaction (3-point response scale for each item: 1 (not satisfied); 2 (satisfied); 3 (very satisfied)). For each subscale, the items were averaged, so that high scores are indicative of satisfaction with the respective feature (potential score range of 1 to 3). Furthermore, the *Psychosocial Adjustment* scale (with its subscales *General Adjustment* (five items), *Social Adjustment* (four items), and *Adjustment to Limitation* (five items; the score was reversed to be comparable to the other adjustment subscales)) was used. Each item was answered using a 4-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree). Items for each subscale were averaged, resulting in a potential score range from 1 to 4).

2.3.2 Experiment

The experiment consisted of three conditions in which participants had to rate the sensory experience of touches applied to the bottom of their feet. Participants were asked to touch one of their soles (which they could freely choose; all participants, however, decided to touch the bottom of the foot contralateral to amputation) in a stroking manner 1) either with

their intact hand (i.e., self-touch condition), 2) their prosthetic hand (i.e., prosthesis-touch condition), or 3) let the present person touch the bottom of the foot in a similar way (i.e., other-touch condition). The exact location where the touch should be applied was given to the participants beforehand using a picture of a sole where the zone of touch had been coloured. Rubber gloves for the participant, the prosthesis, and the allied person were sent in order to standardize the touch experience; however, since equipping the prosthesis with the rubber glove was often not possible, only a minority of participants ($n = 4$) used it. These four participants used the gloves in all experimental conditions, the others were instructed to not using them at all. Participants and their allied persons were asked to practise their stroking movements at the cheek of the participant with the goal to equalise the rhythm and speed of the touch. Since the study aimed at attenuation of touch sensations, standardizing the force of touch is not appropriate; however, participants and allied persons were asked to choose a comparable pressure.

For each condition, the time of touch stroking was set to 30s, and in participants who were guided via telephone, the duration was verbally started and ended by the experimenter. After each condition, participants rated the stimulation in terms of intensity, ticklishness, and pleasantness using a numerical rating scale each ranging from 0 (not at all) to 10 (extremely). The mean value of these three items served as dependent variable (i.e., the *sensory score* measure) for each condition. This measure has repeatedly been used before in the study of sensory attenuation (e.g., Blagrove, Blakemore, & Thayer, 2006; Windt, Harkness, & Lenggenhager, 2014).

2.4 Statistical Analysis

Due to the small sample size, non-parametric tests have been applied. The alpha level in all analyses was .05 throughout the manuscript; if not stated otherwise, we used Bonferroni-correction whenever multiple testing was performed, and the adjusted, exact p -value is indicated by p_{Bonf} . All tests were performed two-tailed. For all our data, we provide

medians (*Mdn*) and interquartile ranges (*IQR*). For each analysis, we further provide test statistics and effect sizes (*r*). All analyses were performed using IBM SPSS v22.

In order to test for perceptual attenuation effects across conditions, Friedman's test was performed on the sensory scores. Post-hoc pairwise comparisons (Wilcoxon Signed Rank tests), using exact statistics, were used to reveal significant differences between conditions. In order to obtain a measure which reflects the similarity of prosthesis-touch to either self-touch or other-touch, we applied following formula to the sensory scores of each participant (PT = prosthesis-touch; ST = self-touch; OT = other-touch):

$$\left(\frac{((|PT-OT|) - (|PT-ST|))}{((|PT-OT|) + (|PT-ST|))} \right)$$

The resulting value (i.e., the sensory similarity index) represents the relative position of prosthesis-touch sensations on a continuum between the poles -1 (other-touch) and +1 (self-touch). Hence, negative values suggest prosthesis-touch being more similar to other touch (with -1 being equal to other-touch) while positive values suggest prosthesis-touch being more similar to self-touch (with +1 being equal to self-touch). 0 would indicate that prosthesis-touch is equally distant to both self- and other-touch. Across the sample, we used a one-sample Wilcoxon-test with the test-value 0 to test whether prosthesis-touch is more shifted to the other- (-1) or self-touch (+1) pole.

We further applied a one-sample Wilcoxon test with the test value 0 to the PEmbS total score in order to test whether prosthesis embodiment is perceived (i.e., a shift of the data to the positive direction). Since the PEmbS was developed and validated using a sample of lower limb amputees (Bekrater-Bodmann, in press), we compared the prosthesis embodiment in our sample of upper limb amputees with the previously reported sample of 118 lower limb amputees using a Mann-Whitney U-test. This enabled us to compare the distribution of prosthesis embodiment data in these two amputee samples.

Finally, we correlated the sensory similarity index with the PEmbS total score using Spearman correlation (with the correlation co-efficient ρ). In order to test for specificity of our

findings, we further applied Spearman correlations to the sensory similarity index in relation to the measures from the TAPES-R.

3 Results

3.1 Experimental data

3.1.1 Sensory score

Across conditions, there was a significant difference for the sensory score data ($\chi^2_{2,13} = 12.27$, $p = .001$). Pairwise post hoc comparisons revealed a significant difference between other-touch ($Mdn = 7.33$, $IQR = 3.17$) and self-touch ($Mdn = 5.00$, $IQR = 4.33$; $z = -2.44$, $p_{Bonf} = .035$, $r = .48$). There also was a significant difference between other-touch and prosthesis-touch ($Mdn = 3.33$, $IQR = 4.33$; $z = -3.05$, $p_{Bonf} = .003$, $r = .60$). However, there was no significant difference between self-touch and prosthesis-touch ($z = -1.82$, $p_{Bonf} = .21$, $r = .36$). Thus, as expected, both immediate and prosthesis-mediated self-touch appeared to be significantly attenuated compared to externally generated touch. Moreover, immediate and prosthesis-mediated self-touch did not differ significantly in sensory scoring. The individual sensory score data are given in Table 2 and the difference between conditions is further visualised in Figure 1.

Figure 1. Sensory score for each condition ($N = 13$). Boxplots indicate interquartile range, whiskers indicate minimum and maximum, and the middle line indicates the median. * Bonferroni-corrected $p < .05$; ** Bonferroni-corrected $p < .01$; ns = not significant.

3.1.2 Sensory similarity index

Testing the sensory similarity index against $Mdn = 0$ revealed that the sensations elicited by prosthesis-touch were significantly shifted towards the positive pole ($Mdn = 0.29$, $IQR = 0.32$; $Z = 2.83$, $p_{\text{Bonf}} = .005$, $r = .78$). This indicates that the sensory score for prosthesis-touch is more similar to the sensory score for self-touch than for other-touch. Individual data for the sensory similarity index are given in Table 2.

3.2 Prosthesis embodiment

Participants predominantly reported significant embodiment experiences for their prostheses ($Mdn = 1.80$, $IQR = 2.73$; $Z = 2.25$, $p = .024$, $r = .75$). Comparing the present data obtained in upper limb amputees with previously reported data obtained in a sample of 118

lower limb amputees ($Mdn = 1.60$, $IQR = 1.33$; (Bekrater-Bodmann, in press)) suggests no significant difference in prosthesis embodiment by the site of amputation ($U = 495.00$, $p = .74$, $r = .03$). Individual data of present prosthesis embodiment is provided in Table 2.

Table 2: Individual data, medians (Mdn), and interquartile range (IQR) for the sensory score, the similarity index, and prosthesis embodiment in the present sample.

Participant #	Sensory score			Sensory similarity index	Prosthesis embodiment
	self-touch	prosthesis- touch	other-touch		
1	5.000	0.000	3.000	-0.250	---
2	3.000	1.333	5.000	0.375	---
3	7.667	3.333	9.333	0.161	---
4	2.000	1.667	5.667	0.846	---
5	7.667	7.000	8.333	0.333	2.900
6	3.333	1.333	7.667	0.520	3.000
7	7.333	5.333	9.000	0.294	2.400
8	3.333	0.667	3.333	0.000	0.800
9	5.333	6.000	7.333	0.333	1.200
10	6.667	7.000	5.667	0.600	2.700
11	2.333	3.667	6.000	0.273	1.800
12	1.667	4.333	8.000	0.158	-0.667 ^a

13	6.000	2.667	8.667	0.286	-0.800
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^a one missing item in the Prosthesis Embodiment Scale

3.3 Relationship between the sensory similarity index and prosthesis embodiment

We found a significant positive relationship between the sensory similarity index and prosthesis embodiment ($\rho = .70$, $p = .036$), indicating that the more the prosthesis is embodied, the more similar is the sensory score from prosthesis-touch to self-touch. This relationship is visualized in Figure 2.

Figure 2: Scatterplot and regression line for the relationship between prosthesis embodiment and the sensory similarity index (Spearman correlation, $n = 9$). ρ = Spearman's rho; p = two-tailed p value

3.4. Specificity of the found relationship

Although the other prosthesis-related variables showed relationships with the sensory similarity index in the same direction as prosthesis embodiment, neither prosthesis satisfaction ($Mdn = 2.00$, $IQR = 0.50$, $\rho = .35$, $p = .36$ for aesthetic satisfaction; $Mdn = 2.00$, $IQR = 0.50$, $\rho = .36$, $p = .34$ for functional satisfaction) nor prosthesis adjustment ($Mdn = 3.60$, $IQR = 1.10$, $\rho = .50$, $p = .17$ for general adjustment; $Mdn = 3.75$, $IQR = 1.38$, $\rho = .03$, $p = .95$ for social adjustment; $Mdn = 1.60$, $IQR = 1.40$, $\rho = .36$, $p = .34$ for adjustment to limitation) had significant associations.

4 Discussion

In the present study, we tested the assumption that self-touch applied through a prosthesis would lead in amputees to comparable sensory attenuation on a perceptual level as non-mediated self-touch through the intact hand. To this end, we included a sample of prosthesis-using upper limb amputees and instructed them to experimentally apply touches to their own foot soles by using either their prosthetic device or their intact hand. In a control condition, the participants were touched by another person. The results indicated that self-touch and prosthesis-touch lead to comparable perceptual attenuation compared to other-touch. Using a similarity index between prosthesis-touch and self- or other-touch respectively, we found a positive relation to prosthesis embodiment, showing the more embodied the prosthesis was, the more similar was the tactile perception to self-touch. This association was specific for prosthesis embodiment, since neither prosthesis satisfaction nor prosthesis adjustment showed a similar relationship. Although the relationship between sensory similarity and prosthesis embodiment has to be considered exploratory due to the small sample size, it provides further evidence that perceptually embodied prostheses can be represented similarly to an actual limb by the users' perceptual system.

The present study's results are in accordance with and extend previous findings. For self-touch as well as for tool-touch, similar levels of sensory attenuation were reported before

(Kilteni & Ehrsson, 2017b). Prostheses can be conceptualized between a biological limb and a tool: while a prosthesis, particularly a functional one, can be considered a tool in terms of empowering its user to interact with the environment, its appearance and function base on the characteristics of an actual limb, which could take over some of the neurofunctional mechanisms of the missing body part. Consequently, there is a long-lasting scientific debate whether prostheses can be more appropriately described as tools or as actual replacements of a lost limb (Murray, 2004; Niedernhuber et al., 2018; Preester, 2011; Preester & Tsakiris, 2009). As Makin et al. (2017) pointed out, one important representational difference between tools and prostheses is that real embodiment – in terms of perceptual incorporation into one's body representation as part of the self – can be achieved for prostheses, but not for tools. Recent results further show that embodiment of a prosthesis is qualitatively comparable to that of an artificial limb in the rubber hand illusion (RHI) paradigm for normally-limbed participants (Bekrater-Bodmann, in press), suggesting that short-termed experimental embodiment and long-termed real-life prosthetic embodiment rely on similar neurocognitive mechanisms. The present findings indicate that the variance in prosthesis embodiment can explain variance in sensory attenuation. Since sensory attenuation is considered reflecting a basic implicit process of self-identification (Bays & Wolpert, 2008), the found relationship provides further evidence that prothesis are, at least in some amputees, represented similarly to real body parts.

4.1 Potential neural underpinnings

What could be the neural basis of the phenomenon? Neurophysiological studies on both the sensory attenuation phenomenon as well as embodiment experiences point to the cerebellum as key player. Imaging studies showed that the cerebellum plays a crucial role in predicting the sensory consequences of movements. By using sophisticated technical devices for the transmission of external or self-generated tactile stimuli, it has been shown that predictable self-touch, compared to unpredictable external touch, is associated with reduced neural activation in the cerebellum (Blakemore et al., 1998, 2001; Shergill et al.,

2013). Comparable modulation of activity in the somatosensory system (Blakemore et al., 1998) and regression of somatosensory responses on cerebellar activity (Blakemore et al., 1999) have been interpreted as cerebellum-mediated attenuation of activity in primary and secondary somatosensory cortex (Blakemore, Wolpert, & Frith, 2000). Kilteni and Ehrsson (2020) complemented these findings by showing that attenuation-related reduced activity in the cerebellum's lobule VI/VIIa and crus I ipsilateral to the touch-receiving body part is functionally connected with the contralateral primary somatosensory cortex, but only if perceptual attenuation is statistically taken into account. This indicates a cerebellum-mediated down-regulation of somatosensory activity underlying perceptual attenuation of self-touch.

Regarding embodiment, studies using conflicting but synchronous multimodal sensory stimulation to induce illusory ownership of an artificial limb showed, among other areas, also an involvement of the cerebellum. Ehrsson et al. found activity in the right cerebellar lobule VI and crus I in a visual RHI paradigm (2004), and the involvement of bilateral lobule VI and crus I/II in a somatosensory-only variant of the RHI (2005). Both a modulation of cerebellar activity when manipulating perceptual embodiment as well as when comparing self- to other-touch might point to a functional relationship grounded in basic self-other distinction. However, it remains unclear why cerebellar activity is reduced in sensory attenuation but enhanced during illusory embodiment. It may be that the sensory conflict induced by the RHI paradigm (i.e., feeling a touch in a non-self object) alerts the cerebellar system which would then actively 'overruled' by cortical regions, ultimately leading to incorporation into the body representation and accompanying embodiment experiences (e.g., Bekrater-Bodmann et al., 2014; Ehrsson et al., 2004; Ehrsson et al., 2005). Following this explanation, the cerebellar activation associated with other-touch (van der Zwaag et al., 2013) could also have at least partly the same neurobiological function, that is, to differentiate between self and other. The modulation of cortical activity accompanying the perception of embodiment might thus modulate cerebellar activation in a top-down manner during prosthesis-touch, accompanied by perceptual alterations in the tactile sensation. Such an effect corroborates evidence

suggesting that hierarchically higher areas can suppress or explain away prediction errors in the cerebellum in a top-down manner (e.g., Cao & Gross, 2015), which is also in accordance with the recently proposed active inference and predictive processing models (Brown, Adams, Parees, Edwards, & Friston, 2013; Friston, 2010) within the free energy framework (Apps & Tsakiris, 2014). Whether or not the recently found difference in cerebellar grey matter in lower limb amputees without a prosthesis compared to prosthesis users and control participants (Di Vita et al., 2018), could be linked to sensory attenuation and prosthesis embodiment, however, remains speculative. Prospective studies have still to elucidate the potential complex interplay between cortical and cerebellar networks for sensory attenuation associated with embodied prostheses.

4.2 Implications for prosthesis development

Next to contributing to current models on sensory attenuation and embodiment, the current results might be of relevance for the more applied field of prosthesis development. Successful RHI induction has been associated with alterations in executed movements (Heed et al., 2011). This effect has been attributed to the recalibration of proprioception (Holmes, Snijders, & Spence, 2006) induced by the spatial discrepancy between one's own occluded and the embodied but visible artificial hand (Mangalam, Cutts, & Frigaszy, 2019). This confirms earlier results suggesting that the peripersonal space representation 'jumps' from the actual hand to the artificial hand when the illusion has been established (Brozzoli, Gentile, & Ehrsson, 2012), which has been proposed to apply as well for embodied prostheses (Bekrater-Bodmann & Foell, 2013). It can be assumed that accompanying effects on motor planning and motor execution might facilitate the interaction between the prosthesis and the environment. Indeed, it has recently been shown that there is a positive relationship between prosthesis embodiment and a reachability judgement task in upper limb amputees (Gouzien et al., 2017), indicating that embodied devices influence the motor behavior of their users. Given the recent efforts on the development of upper limb prostheses equipped with tactile feedback (e.g., Beckerle et al., 2018; Dosen et al., 2015; Nunzio et al., 2017), a

phenomenon related to the attenuation of self-touch might increase in importance: movement-related tactile suppression, that is, the attenuated perception of tactile stimuli on limbs during planning and execution of goal-directed movements (e.g., Chapman, Bushnell, Miron, Duncan, & Lund, 1987; Juravle, Binsted, & Spence, 2017; Voss, Ingram, Wolpert, & Haggard, 2008). This effect reduces the perception and thus the salience of involuntary tactile consequences, for example the contact with an object, during movements, and thus has a comparable function to the attenuation of self-touch, also relying on internal forward models predicting the sensory consequences of movements (e.g., Wolpert & Flanagan, 2001; Wolpert, Ghahramani, & Jordan, 1995). The present study's results suggest that embodiment experiences for the prosthetic device might also have an effect on movement-related tactile suppression or vice versa, which might interfere with motor planning and execution. Thus, future prosthesis developers should particularly focus on the subjective experiences related to prostheses use, since this feature might influence the user's motor behavior.

4.4 Limitations

Several limitations have to be noted. Most importantly maybe, the current sample was small and larger populations should be tested in the future for evaluating generalizability. Larger samples would also enable to address interesting other aspects of prostheses embodiment, such as potential differences between cosmetic and functional prostheses which could not be disentangled here. Nevertheless, the reported effect sizes were large, and the type of prosthesis was descriptively unrelated to sensory attenuation or prosthesis embodiment, tentatively emphasizing that individual stable perceptual traits (Bekrater-Bodmann, Foell, Diers, & Flor, 2012) might be more important than contextual factors. However, there are several experimental factors known to influence embodiment, such as the visual appearance of the artificial object (Tsakiris, Carpenter, James, & Fotopoulou, 2010) or the amount of synchrony of multimodal sensorimotor input (Huynh, Bekrater-Bodmann, Fröhner, Vogt, & Beckerle, 2019), which might help elucidating the causal

underpinnings of the reported effects. For definitive conclusions, however, prospective studies should additionally compare prosthesis-touch with tool-touch, which also has been shown to elicit the sensory attenuation phenomenon (Kilteni & Ehrsson, 2017b). The comparison of both conditions might help to elucidate the role embodiment experiences have for the sensory attenuation of touch.

Furthermore, future studies should better control the application of touch. The here-used home setting in combination with telephone guidance facilitated data collection, but also reduced standardization of sensory input. Previous experiments used sophisticated technical devices for self- or other-touch application with standardized forces (e.g., Shergill et al., 2013; Blakemore et al., 1998; Kilteni & Ehrsson, 2017b), which could also be used for prosthesis-touch. We instructed the participants to match the touch forces as best as they can, which could have introduced a bias especially for the other-touch (Bays, Wolpert, & Flanagan, 2005). However, if so, one would expect a *fainter* other-touch than the found one, due to matching this force to the self-applied (attenuated) touch. The fact that we still revealed the attenuation phenomenon for self-generated compared to other-touch highlights the robustness of our findings. The significant relationship with prosthesis embodiment, although preliminary, further suggests that no substantial bias was involved in our study. However, future studies should substantiate our findings by the assessment of behavioral (e.g., Bays et al., 2005) or neurophysiological measures (e.g., Kilteni & Ehrsson, 2020; Zeller, Litvak, Friston, & Classen, 2015), the latter which might also reveal the proposed interplay between the cerebellum and higher-order cortical regions. This kind of forward and backward dynamics is for which dynamic causal modelling (DCM; Friston, Harrison, & Penny, 2003) has been developed, an analysis technique for testing effective connectivity of reciprocal self-organized systems. Testing different models, the causal link between the cerebellum and the somatosensory system as well other cortical regions involved in embodiment processing could be revealed prospectively. DCM could also be used to model top-down effects of attention (Friston et al., 2003) whose varying levels might affect both prosthesis embodiment and sensory attenuation.

554

555 **4.5 Conclusion**

556 As trivial as the phenomenon of sensory attenuation might be, it gives insight into
557 fundamental neurocognitive principles involved in self-other distinction which is important for
558 successfully interacting with the environment. The present study revealed that upper limb
559 amputees can achieve prosthesis embodiment which in turn predicts perceptual attenuation
560 of self-touch, indicating that at least some amputees can incorporate their prosthesis as
561 replacement for their lost limb. Sensory attenuation might serve as an implicit measure of
562 prosthesis embodiment. Whether or not this phenomenon impacts prosthesis use has to be
563 investigated in the future. If so, this knowledge might influence the development of new
564 prostheses as well as prosthetic rehabilitation programs.

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566

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573

574 **6 Competing interest statement**

575 The authors declare that they have no known competing financial interests or personal
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815 **Supplement**

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Prothesen-Embodiment-Skala für Armamputierte (PEmbS-ULA)

Was für eine Prothese nutzen Sie?

- ☐ kosmetisch ☐ funktionell (myoelektrisch, zuggesteuert, Sauerbruch-Arm, etc.)

☐ Ich habe meine Prothese angelegt.

Anleitung: Bitte sorgen Sie dafür, dass Sie Ihre angelegte Prothese gut sehen können (z.B. durch das Tragen eines T-Shirts). Geben Sie nun für jede der folgenden Aussagen an, wie sehr Sie dieser zustimmen oder diese ablehnen. Wenn Sie einer Aussage zustimmen, kreuzen Sie bitte eine positive Zahl an (1, 2, 3): je positiver die Zahl, desto mehr stimmen Sie der Aussage zu. Wenn Sie eine Aussage ablehnen, kreuzen Sie bitte eine negative Zahl an (-1, -2, -3): je negativer die Zahl, desto mehr lehnen Sie die Aussage ab. Die Null (0) sollen Sie nur auswählen, wenn Sie der Aussage weder zustimmen noch sie ablehnen. Antworten Sie spontan, ohne lange zu überlegen, und lassen Sie keine Aussage aus. Es gibt keine richtigen oder falschen Antworten.

Bitte betrachten Sie nun Ihre Prothese für etwa 60 Sekunden.

☐ Ich habe meine Prothese etwa 60 Sekunden lang betrachtet und bin bereit fortzufahren.

	starke Ablehnung					starke Zustimmung	
1. Ich habe das Gefühl, direkt auf meinen eigenen Arm (meine eigene Hand) zu schauen, und nicht auf eine Prothese.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
2. Die Prothese gehört zu mir.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
3. Ich habe das Gefühl, zwei Arme (Hände) zu besitzen.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
4. Die Prothese ist mein Arm (meine Hand).	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
5. Die Prothese ist ein Teil meines Körpers.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
6. Die Stellung/Haltung der Prothese entspricht der eines echten Arms (einer echten Hand).	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
7. Ich fühle mich körperlich komplett.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
8. Die Prothese befindet sich an der Position, an der sich mein Arm (meine Hand) befinden würde, wenn er (sie) nicht amputiert wäre.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)

Bitte bewegen Sie Ihre Prothese für etwa 30 Sekunden. Wenn Sie eine funktionelle Prothese nutzen, schließen und öffnen Sie bitte die Prothesenhand; wenn Sie eine kosmetische Prothese nutzen, heben und senken Sie diese bitte mit Ihrem Stumpf.

☐ Ich habe meine Prothese für etwa 30 Sekunden bewegt und bin bereit fortzufahren.

	starke Ablehnung				starke Ablehnung		
9. Die Prothese bewegt sich so, wie ich das will.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
10. Ich habe die Kontrolle über die Prothese.	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)

Prosthesis Embodiment Scale for upper limb amputees (PEmbS-ULA)

What kind of prosthesis are you using?

☐ cosmetic ☐ functional (myoelectric, body-powered, Sauerbruch, etc.)

☐ I have put on my prosthesis.

Instruction: Please make sure that you can look directly at your prosthesis (for instance, by wearing a t-shirt). For each of the following statements, please indicate how much you agree or disagree with it. If you agree with the statement, mark one of the positive numbers (1, 2, 3): the more positive the number, the more you agree with the statement. If you disagree with the statement, mark one of the negative numbers (-1, -2, -3): the more negative the number, the more you disagree with the statement. You should select the zero (0) only if you neither agree nor disagree with the statement. Please reply spontaneously, without thinking twice, and do not skip any statement. There are no right or wrong answers.

Please look at your prosthesis for about 60 seconds.

☐ I have looked at my prosthesis for about 60 seconds and I am ready to continue.

	strongly disagree					strongly agree
1. I feel as if I was looking directly at my own arm (hand), rather than at a prosthesis.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
2. The prosthesis belongs to me.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
3. It feels as if I had two arms (hands).	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
4. The prosthesis is my arm (hand).	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
5. The prosthesis is a part of my body.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
6. The posture of the prosthesis corresponds to that of a real arm (hand).	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
7. My body feels complete.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
8. The prosthesis is in the location where I would expect my arm (hand) to be, if it was not amputated.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)

Please move your prosthesis for about 30 seconds. If you are using a functional prosthesis, please close and open the prosthetic hand; if you use a cosmetic prosthesis, please raise and lower it with your residual limb.

☐ I have moved my prosthesis for about 30 seconds and I am ready to continue.

	strongly disagree					strongly agree
9. The prosthesis is moving the way I want it to move.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)
10. I am in control of the prosthesis.	(-3)	(-2)	(-1)	(0)	(1)	(2) (3)