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Full Length Article

Performance among different types of myocontrolled tasks is not related

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ABSTRACT

Studies on myocontrolled assistive technology (AT), such as myoelectric prostheses, as well as rehabilitation practice using myoelectric controlled interfaces, commonly assume the existence of a general myocontrol skill. This is the skill to control myosignals in such a way that they are employable in multiple tasks. If this skill exists, training any myocontrolled task using a certain set of muscles would improve the use of myocontrolled AT when the AT is controlled using these muscles. We examined whether a general myocontrol skill exists in myocontrolled tasks with and without a prosthesis. Unimpaired, right-handed adults used the sEMG of wrist flexors and extensors to perform several tasks in two experiments. In Experiment 1, twelve participants trained a myoelectric prosthesis-simulator task and a myocontrolled serious game for five consecutive days. Performance was compared between tasks and over the course of the training period. In Experiment 2, thirty-one participants performed five myocontrolled tasks consisting of two serious games, two prosthesis-simulator tasks and one digital signal matching task. All tasks were based on tasks currently used in clinical practice or research settings. Kendall rank correlation coefficients were computed to analyze correlations between the performance on different tasks. In Experiment 1 performance on the tasks showed no correlation for multiple outcome measures. Rankings within tasks did not change over the training period. In Experiment 2 performance did not correlate between any of the tasks. Since performance between different tasks did not correlate, results suggest that a general myocontrol skill does not exist and that each myocontrolled task requires a specific skill. Generalization of those findings to amputees using AT should be done with caution since in both experiments unimpaired participants were included. Moreover, training duration in Experiment 2 was short. Our findings indicate that training and assessment methods for myocontrolled AT use should focus on tasks frequently performed in daily life by the individual using the AT instead of merely focusing on training myosignals.

1. Introduction

Assistive technology (AT) takes on an ever greater role in rehabilitation practice, evidenced by the wide scope of ATs currently available, ranging from exoskeletons (Ferris & Lewis, 2009; Mulas, Folgheraiter, & Gini, 2005; Tang et al., 2014) and wheelchairs (Kundu, Mazumder, Lenka, & Bhaumik, 2017; Moon, Lee, Chu, & Mun, 2005; Oonishi, Sehoon, & Hori, 2010) to orthoses (Ferris, Gordon, Sawicki, & Peethambaran, 2006; Sawicki & Ferris, 2009) and prostheses (Geethanjali, 2016; Light, Chappell, Hudgins, &

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Engelhart, 2002; Scheme & Englehart, 2011). AT aids patients in regaining and/or improving their functionality in activities of daily life as well as increasing their independence. In order to actually contribute to patient's functionality and independence, effective and efficient control over AT's is a prerequisite (Valk, Mouton, Otten, & Bongers, 2019), however, this is often a challenge (e.g., Biddiss, Beaton, & Chau, 2007; Biddiss & Chau, 2007a; Biddiss & Chau, 2007b; Engdahl et al., 2015; McFarland, Winkler, Heinemann, Jones, & Esquenazi, 2010; Østlie et al., 2012). AT's are often controlled using biosignals, in particular the signals recorded with surface electromyography (sEMG), also called myosignals, derived at the users´ skin. Although myosignals have previously been studied in an extensive way, and much is known about them, their use as myosignals for controlling ATs requires novel knowledge that is still under development. A key route to gain this knowledge is by studying how myosignals can be assessed and trained. Therefore the current paper focusses on whether there is something like a myocontrol skill that generalizes over different tasks. We take upper limb prostheses as a clinical example of AT since these prostheses are often controlled using myosignals.

The majority of individuals with an upper limb absence, resulting from either an amputation or a congenital deficiency, receive a prosthetic device in order to restore part of their lost functionalities. Often a myoelectric hand prosthesis is chosen as the terminal device. Most of these myoelectric prosthesis hands are controlled using two electrodes that measure myosignals from the muscles of the residual arm. These signals are used to activate the motors inside the prosthesis that move the digits of the hand and sometimes also rotate the wrist (Atzori & Müller, 2015; Behrend, Reizner, Marchessault, & Hammert, 2011; Belter, Segil, Dollar, & Weir, 2013). Conventional prosthetic hands can only perform a tri-pod grip between thumb and index and middle finger while moving in just one joint. Opening and closing of this grip is controlled proportionally, implying that the amplitude of the sEMG is proportionally related to the opening and closing speed of the prosthetic hand. More modern multiarticulating prosthetic hands have active joints in all the digits enabling the use of multiple grip types, such as key grip, fine pinch and cylinder grasp (Atzori & Müller, 2015; Behrend et al., 2011; Belter et al., 2013). Switching between grip types is most often done by producing very specific myosignals, so-called triggers, with the myosignals. These triggers can for example consist of a co-contraction or a double pulse (two short, fast muscle contractions) at respectively both or one of the electrodes. Within a grip type the opening and closing is again controlled proportionally. Note that the use of a prosthesis requires a profound level of control of the myosignals.

In rehabilitation practice the level of skill in proportional control is usually taken as a reference for assessing the quality of myocontrol with the prosthesis. Stated otherwise, it is generally assumed that the degree to which users can proportionally control their myosignals reflects the individual's control over a prosthesis (Dawson, Carey, & Fahimi, 2011; Dupont & Morin, 1994; Gordon & Ferris, 2004). This assumption boils down to the idea that there is something like a 'general myocontrol skill' which is the skill to control myosignals of a specific set of muscles in such a way that those muscles can be employed successfully in a wide range of goal directed tasks, such as controlling different types of AT in different types of tasks. The existence of such a skill would imply that training any myocontrol task would benefit all tasks executed with for instance a myoelectric prosthesis. An example of studies that implicitly assume the existence of a general myocontrol skill are studies using an internal model theory (Antuvan, Ison, & Artemiadis, 2014; Dosen, Markovic, Somer, Graimann, & Farina, 2015; Johnson, Kording, Hargrove, & Sensinger, 2014). According to these studies, in myoelectric prosthesis use only the gain between the produced myosignal and the terminal device, the prosthesis hand, has to be learned. So once there is a fixed mapping between the desired output (i.e., prosthetic hand movement) and the input needed to achieve that output (i.e., myosignals), one should be able to control a prosthesis hand after having learned the gain. Once this inverse model is set up, the prosthetic hand can be controlled independent of the task that needs to be executed. This view is also incorporated in clinical practice where training with the actual prosthesis is preceded by and/or alternated with training of just the myosignal (i.e., the myosignal presented on a computer screen). The idea is that when the gain is the same in those two training tasks, they both contribute to learning the appropriate inverse model. The actual task that needs to be performed with the prosthesis would then again, not matter.

As stated above, the idea of a general myocontrol skill is applied regularly in rehabilitation practice for upper limb prosthesis users, either implicitly or explicitly. This is particularly the case in the field of prosthesis training. Although a large part of rehabilitation training consists of training with an actual prosthesis, a substantial part of the training concentrates on controlling myosignals in a virtual environment. This applies in particular to the pre-prosthetic phase, when the prosthesis has not been manufactured yet but virtual training can be started. Virtual training can have different forms, such as tracing a preprogrammed waveform, steering a virtual car or balancing a scale (Terlaak, Bouwsema, van der Sluis, & Bongers, 2015). Here the (changes in) amplitude of a myosignal that are normally used to control the hand, are used to control the movement of an avatar on the screen. Better performance in the virtual environment implies a better myocontrol skill. The underlying assumption of this training is that the learned general myocontrol skill is also beneficial for controlling an actual prosthesis. However, it has rarely been questioned whether experimental results support the idea of such a general myocontrol skill both specifically for prosthesis use and more generally for myocontrolled AT. As such, we examined whether performance on a series of myocontrolled tasks (performed without a prosthesis) correlates with the performance on prosthesis tasks where in all tasks identical electrodes were used measuring sEMG from identical muscles. For rehabilitation practice, and other fields in which myosignals are used to control AT, the practical implication of results from this study are that if the idea of a general myocontrol skill is supported, only one myocontrol task needs to be trained to improve performance on other myocontrol tasks. However, if myocontrol is task specific, training myocontrolled AT-use should be aimed at the execution of specific tasks that the user wants to master in his daily life.

The relevance of this study does not only come from rehabilitation practice as outlined above. That is, previous research has shown that task specificity plays a role in the performance of upper limb prosthesis use (van Dijk, van der Sluis, van Dijk, & Bongers, 2016a, 2016b). Van Dijk et al. showed that training a task in a virtual environment without using a prosthesis only improved actual prosthesis use if (i) the task performed during training closely resembled the task performed with the prosthesis, and (ii) the provided augmented feedback was aimed at aspects relevant for performing that specific task in daily life. Stated more generally, training appeared to improve performance on a task only if the specific coupling between the action performed and the perceptual information guiding that action was trained (cf. Reed in Meijer & Roth, 1988). This implies that if the coupling between action and perception differs between two tasks, the skill trained in one task will not transfer to the skill needed for the other tasks. Since it is likely that the perception-action coupling differs between the currently used training tasks and actual prosthesis use, it is questionable if training only the myosignal is the proper training for improving prosthesis control. To establish whether myocontrol is a task specific skill, or whether a general myocontrol skill exists, the current paper examines the task-specificity of myocontrol and the differences in individual's performance that have been found for myocontrol tasks (cf. Bouwsema, van der Sluis, & Bongers, 2010), and in other motor tasks (Cesqui, d'Avella, Portone, & Lacquaniti, 2012; Golenia, Schoemaker, Mouton, & Bongers, 2014; Rop & Withagen, 2014; Vegter, Lamoth, de Groot, Veeger, & van der Woude, 2014; Withagen & van Wermeskerken, 2009).

Now imagine a skill-continuum that ranks all the possible outcomes between the poorest and best performers. If a general myocontrol skill exists, we expect that participants who show good (or poor) control and thus a high relative ranking in one myocontrol task, show comparable performance and thus approximately the same relative position on the skill-continuum in other myocontrol tasks. That is, the results support a general myocontrol skill if the correlation between rankings of individuals over tasks is high. If this is the case, training of the myocontrol skill boils down to training the production of proper myosignals, which can be done using any myocontrol task. In contrast, if myocontrol is task specific, someone who performs well on one myocontrol task, will not automatically perform well on another myocontrol task. Under this condition, ranking the performance of individuals will be specific for each task, resulting in low correlations between rankings of different tasks. The ranking of a participant in a certain task might not just depend on the general myocontrol skill or the task specific skill, but also depends on the participants' experience with performing myocontrol tasks. It is known that performance in a myocontrol task can be improved by training (Bouwsema et al., 2010a; Østlie et al., 2012; Resnik et al., 2012; Terlaak et al., 2015; van Dijk et al., 2016a, 2016b) and therefore, we also investigated the effects of training on the ranking of participants' performance on myocontrol tasks.

2. Experiment 1

2.1. Methods

2.1.1. Participants

All participants were 18 years or older, right handed, had normal or corrected to normal vision, were free of any (history of) disorders of the arms and upper body and had no prior experience in using a myoelectric device. The experiment was performed at the Center for Human Movement Sciences of the University Medical Center Groningen, The Netherlands, approved by the local ethics committee and included in the Dutch trial register (NTR5593). Written informed consent was obtained from all participants prior to the start of the experiment. After signing the informed consent participants filled out a questionnaire on overall gaming experience. A questionnaire on how motivated participants were while performing the myogame task was conducted on day 1 and day 5 after the training. All participants received a gift voucher after they completed the measurements.

2.1.2. Materials

Two tasks were performed; 1) in the compressible objects (CO) task participants had to grasp compressible objects with a myoelectric upper-extremity prosthesis simulator, and 2) in the adaptive catching (AC) task participants had to play a videogame using the sEMG of muscles in the forearm to control a grabber with which they had to grasp an object that fell from the top of the screen.

During the Compressible Object (CO) task participants wore a myoelectric upper-extremity prosthesis simulator, which resembled a transradial prosthesis as closely as possible (Fig. 1A; see also (Bouwsema, van der Sluis, & Bongers, 2014) and (Romkema, Bongers, & van der Sluis, 2013)). A myoelectric hand was attached to a shell socket in which the sound hand could be placed, and connected to

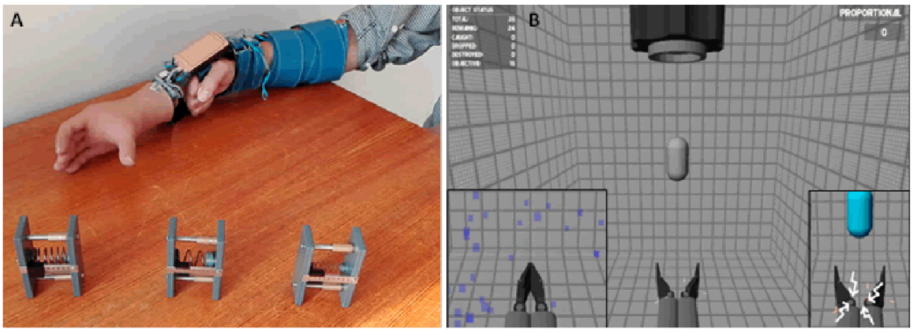

Fig. 1. Layout of the tasks. 1A: Compressible Objects (CO) task. The myoelectric upper-extremity prosthesis simulator and the three compressible objects consisting of two plates coupled by a spring, two sliders and a caliper are shown. 1B: Adaptive Catching (AC) task. Objects fall towards a grabber. Closing too forcefully will break the object (left bottom corner), opening too far will break the grabber, indicated by sparks, and make it force-close (right bottom corner).

a splint that was adjustable in length. The simulator was attached to the forearm with a Velcro sleeve. Two sEMG electrodes (13E200 electrodes, MyoBock, Otto Bock Healthcare products, Austria) were placed in the shell socket. Their location could be adjusted so that they could be placed on the major muscle bellies of the flexors and extensors of the wrist. The myoelectric hand was a MyoHand VariPlus Speed (Otto Bock Healthcare products, Austria) with proportional speed (15–300 mm/s) and grip force control (0-~100 N). The aperture of the prosthetic hand was measured using a goniometer (Cermet PC300 potentiometer, Contelec, Switzerland), of which one leg was attached to the thumb and the other leg was attached to the index finger of the prosthetic hand. This goniometer was connected to a NI-USB 6009 data acquisition device (National Instruments Corporation, USA) and sampled the angle of the hand at 2000 Hz. Between picking up the objects the hand rested on a pressure sensor that was connected to the same NI-USB 6009 data acquisition device and sampled the pressure of the hand on the plate at 2000 Hz. The measured data was sent for storage to the laptop computer (ASUS, 64-bit, Windows 8).

The objects to be picked up were three compressible objects, all consisting of two plates coupled by a spring and two sliders ((6 × 3.5 × 9 cm), Fig. 1A). The resistance of the springs differed per object (low resistance 0.49 N/mm, moderate resistance 2.38 N/mm and high resistance 4.32 N/mm). The maximum amount of compression (in mm) was measured using a caliper mounted on the compressible objects (Fig. 1A).

In the Adaptive Catching (AC) task, the myogame was controlled using two electrodes (13E200 electrodes, MyoBock, Otto Bock Healthcare products, Austria) placed on the most prominent muscle bellies of the flexors and extensors of the wrist. In order to minimize the differences in delay between the muscle contraction and the action of the end effector between the two tasks, the same electrodes were used in both tasks. These electrodes were connected to a desktop computer via a Porti-5 data acquisition device (TMS International, The Netherlands, sample rate 500 Hz). The signal was calibrated to the highest value and scaled between 0 and 1 (see Procedure). The scaled signal was fed from the desktop computer (HP, 32-bit, Windows XP) to a laptop computer (same as in CO) via UDP at 100 Hz.

During the AC task, falling objects had to be caught with a virtual grabber (Fig. 1B). The speed of the opening and closing of the grabber was proportionally related to the magnitude of the scaled sEMG signal, to resemble the functioning of a prosthesis. The sEMG signal of the extensors and flexors of the wrist were used to open and close the grabber, respectively. The objects, all randomly sized between a fixed minimum and maximum size, fell straight down from a cannon at the top of the screen. In the game participants received feedback (see Procedure) about the width of the opening of the grabber relative to the object size and the closing speed, making it an adaptive catching task.

2.1.3. Procedure

Each session of CO began with palpating the most prominent muscles bellies of the extensors and flexors of the wrist, after which the prosthesis simulator was fitted. Subsequently participants could test whether they were able to open and close the hand easily. If not, the prosthesis was fitted again and/or the gain of the electrodes was increased. Participants once opened the hand maximally in order to calibrate the goniometer. They were instructed to pick up the object placed in front of them and lift it about 10 cm while compressing the object as little as possible. At the start of each reach the hand of the simulator was closed and placed on a pressure sensor. The object was placed diagonally at 15 cm left from the hand at an angle of 45°. After hearing a beep, participants lifted the hand and moved up the object.

Each AC session began with the fitting of the electrodes after palpating the most prominent muscle bellies. To calibrate the sEMG signals, participants were asked to flex and extend their wrist slowly until they reached their maximal force. The maximum amplitude of the sEMG for both signals was used to normalize the sEMG signals between 0 and 1, matching the maximum opening and closing speed of the grabber. Participants were instructed to avoid crushing the objects by closing the grabber at the appropriate time and also at the appropriate speed. In this way the AC task mimicked the CO task. The objects to be caught came in three different shapes (diamond, square, and ellipse) and three different colors (red, light blue, or blue) that indicated the three levels of breakability (easy, medium or hard, respectively). Feedback was given on the aperture of the grabber; if this aperture exceeded 1.5 times the diameter of the object, the grabber would visually start to vibrate and give off sparks (Fig. 1A). Furthermore, opening the grabber 1.7 times the diameter of the object would cause it to close rapidly, making it impossible to catch the object. Participants were therefore also instructed to scale their hand opening to the objects. Training with this embedded augmented feedback will ensure transfer of the learned behavior from the game to actual prosthesis use (van Dijk et al., 2016b).

2.1.4. Design

Experiment 1 was conducted on 5 consecutive days. On each day participants trained both tasks for 12 min each. The order of the tasks was counterbalanced over all participants. We call each day a session, and each set of repetitions of 25 pick-ups or falling objects a block. If the 12 min had passed before a block was finished, the block was ended prematurely and not used for further analyses. The order of the compressible objects in CO and the order of the falling objects in AC were randomized. The first block of day 1 was used as the pre-test measurement, the last completed block on day 5 as a post-test measurement. On day 1 all participants were asked to fill in a questionnaire on their gaming experience. A questionnaire on motivational aspects regarding the research tasks was conducted on day 1 and day 5.

2.1.5. Outcome measures

Customized Matlab (2014b, The Mathworks Inc., USA) scripts were used to calculate four different outcome measures.

2.1.5.1. Compression – CO task. For CO we measured the maximum compression of the compressible objects, using the caliper which

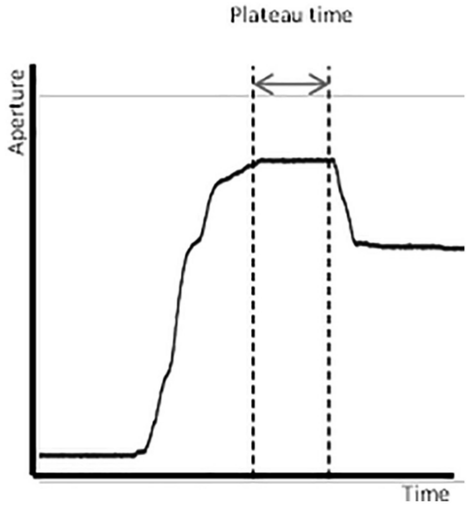

Fig. 2. Representation of the plateau time. The aperture profile is shown over time. Over time the hand opens to grasp the object, then closes to fixate it. The plateau time can be found between the dashed bars. It is the time from the end of the hand opening to the start of the hand closing when grasping an object.

was mounted on the compressible objects. Only the object with the least resistance was taken into account for data analysis, since for this object the largest differences were expected between good and poor performers.

2.1.5.2. Plateau time – CO and AC task. During a grasping task with a prosthetic hand/virtual grabber, after the start of hand opening, the aperture of the hand shows a plateau at which the hand aperture does not change for a while. This time span is called the plateau time (Fig. 2). This measure has proven to be of importance in prosthesis use (Bouwsema et al., 2014; Bouwsema, Kyberd, Hill, van der Sluis, & Bongers, 2012; Bouwsema, van der Sluis, & Bongers, 2010b). For example; smaller plateau times correlated with higher scores on the Southampton Hand Assessment Procedure (Light, Chappell, & Kyberd, 2002) scores in experience prosthesis users (Bouwsema et al., 2012)

2.1.5.3. Aperture gap – AC task. For AC, the difference between maximum aperture and the size of the falling object, hereafter called aperture gap, was measured. This gap will be larger when the hand/grabber is not accurately scaled to the object that needs to be caught or grasped. This measure was chosen because of its relevance in grasping objects both with a prosthesis and in a virtual environment (Bouwsema et al., 2010b; van Dijk et al., 2016a, 2016b). All objects were taken into account in the data analyses.

2.1.5.4. Differences day 1 and day 5. In order to assess if and how much participants improved their performance over the course of the training sessions, we computed the differences between the averages of the outcomes of day 1 and day 5. The difference measures used in the analyses were defined as (1) the difference of the mean compression of the smallest object for CO and (2) the difference of the aperture gap averaged over the three object sizes AC. Both differences were normalized to the value of day 1.

2.1.6. Data analysis

Per task and outcome measure the participants were ranked based on their performance on that outcome measure. For both CO and AC only completed blocks, blocks in which all 25 repetitions were performed, were taken into account. Repeated measures ANOVA's were performed to look at improvement between day 1 and day 5, dependent variables were Compression, Aperture gap and Plateau time. A signal to noise ratio was calculated for Compression, Aperture gap and Plateau time on day 1 and 5. Signal to noise ratios were calculated as a coefficient of variation (the mean divided by the standard deviation), a higher signal to noise ratio indicates more variation. Kendall rank correlation coefficients (Kendall's tau) were computed to analyze the relative performance on the two tasks (cf. (Howell, 2013)). Additional Kendall rank correlations were computed to analyze whether ranking of the participants' individual performances within a task changed over the course of several training days. *P*-values smaller than 0.05 were considered to be statistically significant.

2.2. Results of experiment 1

Twelve participants; two men and 10 women were included in experiment 1. The results of one participant were excluded from analysis, since this person did not perform the task as instructed. The participant did not understand the repeatedly given instructions about compressing the objects as little as possible. The mean age of the remaining 11 participants was 23.1 years (SD 2.4). For CO, 1 block was completed per session (SD 0), for AC on average 6.9 blocks were completed per session (SD 0.38). On average, the participants played videogames for 2.8 h a week (range of 0–20 h). Motivation between the first and fifth day of training did not differ

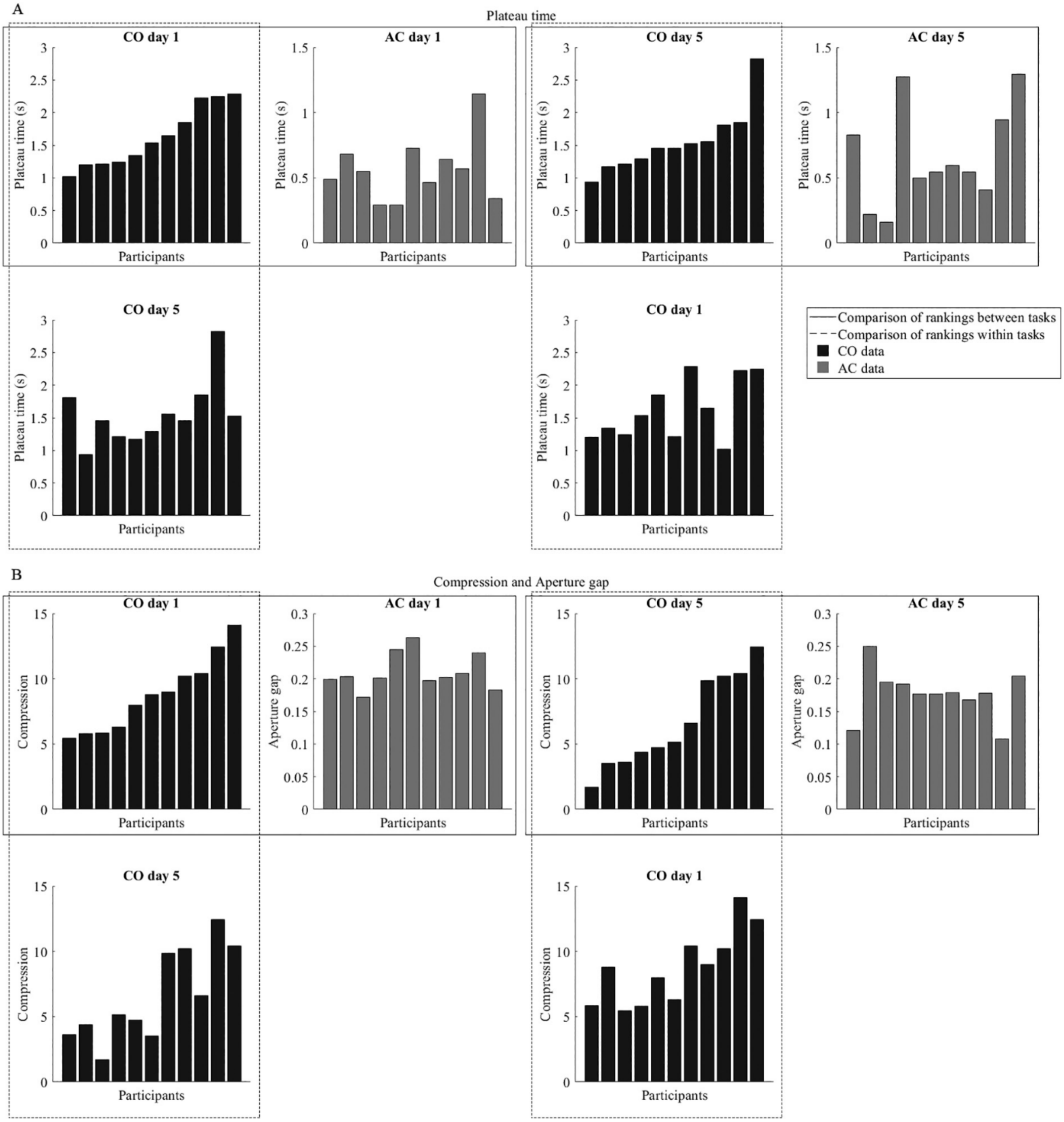

Fig. 3. Results of comparing Plateau time and Aperture/Compression measures for CO and AC. *A: Plateau time;* Ranking of participants using plateau time results of CO task at day 1 (left block) and at day 5 (right block) as a reference. The solid, horizontally oriented boxes show the comparison of the participants' ranking on both tasks for day 1 and day 5. Here the black bar shows the sorted ranking of participants on the CO task, the grey bar plot represents the ranking on the AC task, ordered based on the ranking on the CO task. These plots show the discrepancies between performances on both tasks. The dotted vertically oriented boxes show the comparison between day 1 and day 5 within a task, here can be seen that the ranking remains more or less similar over days. *B: Compression and Aperture gap;* Ranking of participants using Compression of the CO task at day 1 and at day 5 as a reference. The bar plots are set up as in 3A. Here again a lack of resemblance between the tasks within the days can be seen. In the dotted boxes the relative stable ranking within the compression for the CO over days can be seen.

significantly.

2.2.1. Comparison between CO and AC

2.2.1.1. Correlations between tasks. First, the ranks on plateau time for both CO and AC were compared: we did not find a correlation on day 1 ($\tau = 0.09, p = .76$) nor on day 5 ($\tau = 0.27, p = .28$, see horizontal rows in Fig. 3A). Comparable results were found for the ranks on Compression (CO) and Aperture gap (AC). No correlation between the tasks was found on day 1 ($\tau = 0.13, p = .65$) nor on

Table 1
Variation and signal to noise ratio day 1 and 5.

	Compression	Day 5	Plateau Time CO	Day 5	Aperture Gap	Day 5	Plateau time AC	Day 5
	Day 1		Day 1		Day 1		Day 1	
Median	8.78	5.17	1.52	1.55	0.20	0.18	0.46	0.60
Standard deviation	2.87	3.53	0.53	0.72	0.03	0.04	0.29	0.35
Mean	8.76	6.61	1.73	1.73	0.21	0.18	0.56	0.64
Signal to noise ratio	3.06	1.87	3.26	2.40	7.74	4.70	1.96	1.84

Median, standard deviation, mean and signal to noise ratio.

day 5 ($\tau = -0{,}16$ $p = .54$, see horizontal rows in Fig. 3B).

2.2.1.2. Correlations between the rankings within the tasks over time. Most of the participants improved over time: CO; Compression (F (1,10) = 12,91, $p < 0{,}01$), AC; Aperture gap (F(1,10) = 23,71, $p < .005$), but no significant improvement was seen for the Plateau time. To make sure that Kendall's tau could be used median, mean, standard deviation and signal to noise ratio of the four outcome measures on day 1 and day 5 was computed (Table 1). The data show enough spread over participants to apply a correlational measure. When looking at the participants' ranking they did not significantly differ over the course of the 5 training days in both the CO task and the AC task. The vertical, dotted, boxes in Fig. 3A show the difference in ranking within the task for the CO measures. Here all bars in the bar plot that are vertically aligned, represent the same individual. To give more information about the development over the 5 training days, the correlations for Compression (CO) and Aperture gap (AC) are shown in Table 2.

2.2.1.3. Differences day 1 and day 5. In Fig. 4 the difference between performance on day 1 and day 5 is shown for each individual participant. Large differences between individuals showed up for both Compression in CO and the Aperture gap in AC. No significant correlation was found ($\tau = 0.02$, $p = 1$) between the rankings of the tasks based on improvement between the first and the last training day.

2.3. Discussion of experiment 1

The rankings of the participants did not correlate for the two outcome measures after executing two different myocontrolled tasks. Also the difference between the performance on Day 1 and Day 5 did not correlate for the two tasks. Furthermore, a training period of 5 consecutive days did not change the ranking of the participants showing that there was consistency in the behavior of participants on both tasks. If a general myocontrol skill existed, we would have expected the participants' rankings to be similar across tasks and the difference in performance between day 1 and day 5 to correlate over tasks. Therefore, our findings are not in line with the idea of a general myocontrol skill.

These differences in the participants' ranking between tasks might be explained by the number of training trials that was lower in the CO task compared to the AC task. It takes more time to pick up 25 objects with the prosthesis simulator than catching 25 objects on the screen. To examine whether the results were affected by this number of training trials, we performed a similar analysis as above between day 5 of CO and day 1 of AC (the number of trials was comparable at these times). Interestingly, we again found no correlation between the tasks. This indicates the difference in number of training trials between tasks did not affect our findings.

Before we interpret our findings in a larger context it is important to ensure that the findings are not specific to the two tasks used in the current experiment. Therefore, we performed a second experiment in which a broader range of tasks was compared. Since Experiment 1 showed that training did not affect the participants' ranking, Experiment 2 was performed in one session and without a training period.

Table 2
Comparison of the ranking on all 5 training days.

CO	Day 1	Day 2	Day 3	Day 4	Day 5	AC	Day 1	Day 2	Day 3	Day 4	Day 5
Day 1		0.75*	0.35	0.49*	0.64*	Day 1		0.60*	0.60*	0.64*	0.56*
Day 2	< 0.001		0.16	0.60*	0.60*	Day 2	0.01		0.78*	0.60*	0.60*
Day 3	0.16	0.54		0.35	0.27	Day 3	0.01	< 0.001		0.60*	0.75*
Day 4	0.04	0.01	0.16		0.56*	Day 4	0.006	0.01	0.01		0.78*
Day 5	0.006	0.01	0.28	0.02		Day 5	0.02	0.01	< 0.001	< 0.001	

Left: CO. Above diagonal; τ-values. *: $p < .05$. Below diagonal; p-values. Right; AC. Above diagonal; τ-values. *: p < .05. Below diagonal; p-values.

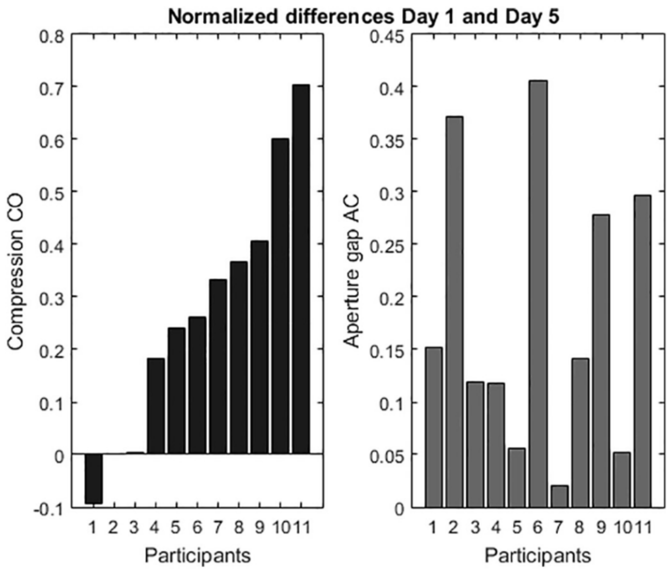

Fig. 4. Ranking of the normalized differences between day 1 and day 5. Compression for CO (left) and aperture gap for AC (right). The improvement on both tasks are sorted based on the CO task.

3. Experiment 2

3.1. Methods

3.1.1. Participants

The location were the study was conducted, the eligibility criteria of participants, and the protocol for informed consent were the same as in Experiment 1. The experiment was approved by the local ethics committee and was included in the Dutch trial register (NTR5280).

3.1.2. Materials

Five tasks were performed; two prosthesis simulator tasks during which (1) cylinders had to be grasped, henceforth named Cylinder Grasping (CylGr, Fig. 5), and (2) the prosthesis hand had to be opened and closed at different speeds, henceforth named Prosthesis Speed Control (SpeedCont). Two serious games; consisting of (3) a free catching (FreeCa) task and (4) a Following Task (FollT, Fig. 5), which will be explained in the below. During the last task (5) a pre-programmed line on a computer screen had to be matched with the EMG signal, using either the extensors or the flexors of the wrist, this task was named Tracking Task (TracT, Fig. 5). Both the prosthesis tasks (CylGr, SpeedCont) and the myogames (FollT, FreeCa) were controlled in a similar way as the tasks in Experiment 1 were controlled. In all tasks the same electrodes were used.

During CylGr, three wooden cylinders with a height of 10 cm and a diameter of either 2 cm (small), 4 cm (medium) or 6 cm (large) were grasped. During SpeedCont the prosthetic hand had to be opened at three different speeds; slow, intermediate and fast. For both CylGr and SpeedCont a goniometer was attached to the prosthetic hand as was done in Experiment 1 in the CO task.

The FreeCa myogame was similar to the AC game of Experiment 1 without the feedback on the aperture and closing force.

The FollT consisted of a moving light beam that had to be followed by using a platform controlled by the myosignal. The beam moved at three different speeds and these speeds were proportional to the EMG at 15%, 30% and 45% of the participants' maximum EMG amplitude. Participants received visual feedback on their performance. Positive feedback was given in the form of a lightning bolt that appeared if the light beam hit the middle of the platform (boundaries at −5% and 5% of the width of the beam) and if the

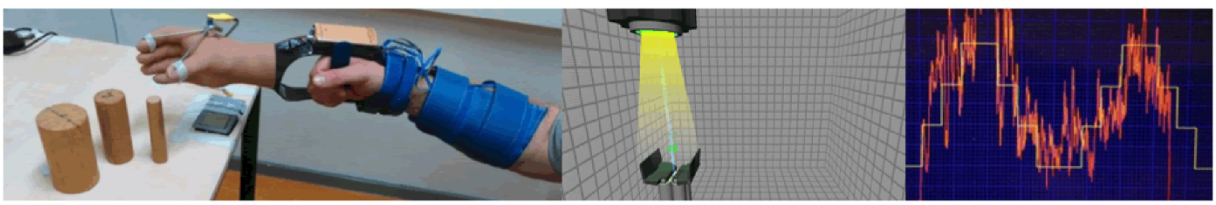

Fig. 5. Example of the tasks. Left: CylGr; The three different cylinders and the prosthesis simulator with goniometer attached. Middle: FollT; layout of the light following game. Right: TracT; The pre-programmed line in yellow and the EMG in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

following was performed at the correct speed. In addition, participants were awarded points when the platform stayed within the total width of the light beam. If the center of the platform passed either side of the light beam points were subtracted.

During the TracT task and the FollT the electrodes were connected to the same laptop computer as used in Experiment 1 via a NI-USB 6009 data acquisition device (National Instruments Corporation, USA) that sampled at 2000 Hz (PEMG). In this case custom made LabView software (National Instruments Corporation, USA) with the same filter setting as described in Experiment 1 for the AC task was used.

3.1.3. *Design and procedure*

Experiment 2 was conducted in one session in which all five tasks were performed in a randomized order. Before starting a task, instructions about that task were given. Subjects were allowed a maximum of five practice movements per task to get adjusted to the task.

Each task consisted of one block of 15 repetitions: in CylGr 15 objects were grasped, in SpeedCont 15 opening/closing cycles were performed, 15 objects were dropped in FreeCa and 15 following movements were made in FollT. In TracT 3 pre-programmed lines had to be followed twice, first with the myosignal of the extensors of the wrist and the second time with the flexors of the wrist.

At the beginning of the sessions of CylGr and SpeedCont the goniometer had to be calibrated (see CO task of Experiment 1). In CylGr the objects were presented in semi-random order, ensuring that all three objects were grasped five times. For SpeedCont, participants started their task after hearing a beep. The participants were instructed to fully open and close the hand at three different speeds; slow, intermediate and fast (without grasping an object). The repetitions were made in semi-random order, ensuring that all three speeds were performed five times. The serious games (FreeCa, FollT) were calibrated like the AC task in experiment 1. For FollT the maximum EMG, calibrated as 1, equaled the maximum moving speed of the platform. The TracT task was calibrated in the same way as the other myogames. The maximum amplitude of both EMG signals was determined and the signals were normalized. The maximum amplitude asked during the task was always less than 91% of the maximum amplitude (equals 0.9).

3.1.4. *Outcome measures*

Customized Matlab (2014b, The Mathworks Inc., USA) scripts were used to calculate one outcome measure per task.

3.1.4.1. CylGr - aperture hand. The outcome measure for CylGr was the normalized difference between the diameter of the cylinder (object size) and the aperture of the prosthetic hand in percentage of the maximal hand opening. This outcome measure is called the Aperture gap. The Aperture gap was averaged over the 15 objects.

3.1.4.2. CylGr - speed hand. For SpeedCont the movement speed of the three requested velocities (slow, intermediate, fast) was measured. The slope of the least square line over the mean delivered speed per requested velocity was determined (see Bouwsema, van der Sluis, et al., 2010).

3.1.4.3. FreeCa - aperture grabber. For FreeCa the outcome measure was the difference between the object size and the aperture of the grabber called the Aperture gap. The average aperture gap over the 15 objects was determined.

3.1.4.4. FollT - speed platform. Outcomes of FollT were determined as in SpeedCont.

3.1.4.5. TracT - error amplitude. During TracT the goal was to minimize the error between the requested and delivered EMG amplitudes in all six repetitions. Per repetition the mean error was calculated. The mean of the six mean errors was used in the analyses.

3.1.5. *Data analysis*

The data-analysis was performed as described in experiment 1. The statistical analysis consisted of Kendall rank correlation coefficients between all tasks, resulting in a cross correlation table.

3.2. *Results of experiment 2*

Thirty-two participants (mean age 22.4 (SD 7.6) y); twelve men and twenty women were included in experiment 2. One outlier (< 1st quartile – (1,5*Inter quartile range) or > 3rd quartile + (1,5*Inter quartile range)) was excluded from all analyses. This outlier fell below the range on 4 of the 5 tasks. Task performance is presented in Table 3.

None of the participants' rankings on task performance correlated (Table 2), indicating that individuals performing well in one task did not necessarily perform well in any of the other tasks. The correlation between the rankings of three tasks (CylGr versus SpeedCont and SpeedCont versus FollT) had *p*-values below 0.1 but even if the threshold of significance was extended to 0.1 the τ-values of those correlations showed that they would be fairly weak.

3.3. *Discussion of experiment 2*

None of the participants' rankings in the tasks of Experiment 2 correlated. If a general myocontrol skill existed we had expected to find a high correlation between the participants' rankings on the different tasks. As such, the results Experiment 2 confirmed the

Table 3
Results comparison experiment 2.

	Mean (SD)	CylGr	SpeedCont	FreeCa	FollT	TracT
CylGr (% of max. aperture)	39.03 (20.875)		−0.23	0.13	−0.03	0.13
SpeedCont (slope)	14.56 (4.02)	0.08		< 0.01	0.23	0.06
FreeCa (Δ pixels)	0.39 (0.17)	0.29	1		−0.06	0.19
FollT (slope)	0.71 (0.21)	0.84	0.08	0.66		−0.07
TracT (Δ amplitude)	0.09 (0.09)	0.33	0.64	0.14	0.61	

Second column: means and standard deviations for all five tasks. Third - seventh column: Cross correlations between all tasks. Above diagonal; τ-values. Below diagonal;. p-values.

conclusion of Experiment 1.

4. General discussion

We tested whether there exists a general myocontrol skill that underlies a series of tasks that are controlled using the sEMG of the same set of muscles. Since myocontrol over an external system is a novel task there is a possibility that such a skill of myocontrol emerges during practice, therefor we looked at performance both before and after a period of training two tasks (Experiment 1). We did not find any correlations between performance of participants on these tasks both before and after training. We did find that people improved their performance after a period of training, interestingly however, this did not affect their ranking within the tasks since the rankings within both tasks over the days did correlate. This correlation was stronger in the AC task but it was also present in the CO task. To exclude that the absence of correlation between the two tasks was biased by the choice of the particular tasks, we ran Experiment 2 in which we examined more and different tasks. Again, we did not find any correlations between the participants' performance on the tasks. Based on the results of the two experiments we take our findings to indicate that a general myocontrol skill does not exist, at least not for the tasks we measured, the training period we used, and the outcome measures we used.

4.1. Myocontrol as a skill

Applying the internal model as described in the introduction section would mean that once myosignals can be controlled properly, they can be used to perform any task. This would imply that the level of control over the myosignals does not differ between different tasks. Our results however question the existence of such a general skill and suggest that further explanations are needed.

Our results are more consistent with the theory of action systems or the action-perception theory as earlier described for motor learning (Meijer & Roth, 1988; Rieser, Pick, Ashmead, & Garing, 1995). Within these theories there is a tight coupling between information guiding the movement and the action itself. In our case that would mean that people perform a myocontrolled task using a specific action-perception coupling between the perceptual information guiding the task performance and end-effector movement (i.e., prosthesis or avatar in game). Furthermore, our findings suggest that (i) this action-perception coupling differs between myocontrolled tasks, and (ii) participants who are good in picking up and using this information in one myocontrolled task are not necessarily performing comparably in another myocontrolled task. This means that the coupling between the action and the perception is very task specific. (van Dijk et al., 2016a, 2016b) showed the importance of the specifics of a task when training to improve prosthesis use. They found that improvement in prosthesis use is only achieved if the specifics of the trained task are the same as the specifics of the prosthesis task. This could explain the lack of correlation between the performance on all the performed tasks in our study. The tasks differed in their goal even though they were similar with respect to the myocontrolled interface used.

4.2. Implications for myocontrolled AT

The results of our experiments show that we have to rethink the way current training methods and, eventually, testing methods of myocontrolled tasks employed in training AT use need to be set up. We did not find a correlation between fairly simple, isolated tasks. We assume that the correlation will also be absent for more complex (daily life) tasks consisting of a sequence of movements, because the movements making up the tasks will also each have their own action-perception coupling. Our current results were found in tasks used mostly early in prosthetic rehabilitation. We expect that similar effects will be found in more functional tasks such as the SHAP (Light et al., 2002), box and blocks test (Mathiowetz, Volland, Kashman, & Weber, 1985), refined clothespin test (Hussaini & Kyberd, 2017) or Cubbies task (Kuiken, Miller, Turner, & Hargrove, 2016) which are often used to determine level of skill in prosthetic rehabilitation. Since the action-perception coupling between these tasks also differs we expect similar results.

Currently, individuals with an amputation are often still training with simple task such as following lines with visualized EMG signals on a computer screen. Our results show that performance on these simple tasks will not correlate with performance on actual prosthesis use. Based on our findings we suggest that both training methods and assessments need to be focused on tasks that are frequently performed in the daily life of the individuals with an amputation. Since it is impossible to capture all possible tasks in training or testing set we advise to focus on very common, often used tasks such as reaching for and grasping an object, manipulating and releasing an object which is used for e.g. eating and drinking (Cordella et al., 2016). While we took arm prosthetics as an example of AT, we think the findings will hold for all ATs that are controlled using myocontrol. In all cases the task that has to be performed with the terminal device (a specific AT) should be trained is such a way that the correct action-perception coupling arises. We could not find any specific literature about the transfer of skill from myocontrolled AT training to actual use of AT in daily life. Our findings could be a first step in creating more structured and detailed knowledge about how to train myocontrolled AT.

4.3. Serious gaming for learning myocontrol

In both of our experiments serious games were included. Serious games are developed to be an entertaining way to teach its players a new skill, such as actively using AT. Besides being entertaining, another advantage of using serious games is that training can be started in the period between losing a certain function or ability and receiving the AT designed to regain or improve the lost functionality, since it only requires the ability to produce myosignals. For prosthesis use (van Dijk et al., 2016a) showed that serious games can be used to improve certain aspects of prosthesis use, as long as the trained tasks are very similar to the tasks that have to be performed in daily life, both in goal as in the information and feedback the player perceives. One disadvantage of serious games that could be of influence on the lack of correlations between the tested serious games and the prosthesis tasks in our study could be the anatomically incorrect relationship between position of the limb producing the signal and the avatar on the screen. This problem could be avoided by combining virtual reality with serious gaming. Several initiatives have been taken with virtually adding an arm prosthesis onto the stump of an amputee, who subsequently performed a task in a virtual environment (Blana, Kyriacou, Lambrecht, & Chadwick, 2016; Lambrecht, Pulliam, & Kirsch, 2011; Snow, Loureiro, & Comley, 2014). By combining this technique with serious gaming both the anatomical correctness, the relevant information and the entertainment can be captured in one method. If this combination of virtual reality and serious games can mimic the task that has to be performed in daily life very closely, action-perception coupling might be similar in these tasks. Eventually, this might result in rankings among participants to be similar between such a gaming task and actual AT use, which could offer possibilities for using these virtual reality presented games as training and testing tools. An additional advantage of using such a training and testing game is that it can be customized to suit the needs of individual patients, making this method well suited for personalized medicine.

4.4. Limitations

An important limitation of both experiments was the inclusion of unimpaired adults. Generalization to individuals with an amputation or other deficiency should be handled with caution. However, previous research has indicated that the use of prosthesis simulators is comparable with the use of a real prosthesis for both performance measures and kinematic profiles (Bouwsema et al., 2010b). Furthermore it should be noted that we cannot rule out that the training period used in Experiment 1 was too short. However, from previous research in serious gaming using sEMG (van Dijk et al., 2016b) we know that transfer, and thus improvement in virtual and actual prosthesis tasks, was achieved after a similar amount of training time.

In both experiments we used Kendall rank correlations. By only looking at ranks, information about motivation, ambition, understanding of the task and previous experience is lost. However, during all measurements two test leaders were present. They instructed the participants and made sure the tasks were understood. Furthermore, a questionnaire on gaming experience was conducted prior to Experiment 1 and a questionnaire requiring after motivation at the first and last day of training in Experiment 1 did not show significant differences. We therefore argue to have minimized the effects of motivation etc.

During this study we made use of 7 short, largely ballistic tasks. Generalizing the conclusions to other tasks should be done with caution. However, since no correlation was found even in very similar tasks, we expect that the results will also be found for other simple tasks. We chose to simplify the tasks in order to be able to look into basic prosthesis control. Correlation between performance on more complex or functional tasks might differ from our findings.

5. Conclusion

The findings do not support the existence of a general myocontrol skill that underlies tasks that are performed using the same musculature. We did not find correlations between rankings of performance of participants in different tasks related to prosthesis use that were all controlled using the sEMG of the flexors and extensors of the wrist. We also did not find differences after a training period. We interpret our results such that transfer of skill between tasks is only possible when the coupling between action and perception is the same between those tasks. Current practice in rehabilitation where training and assessment is often in different tasks in which the myocontrolled AT is used in daily life might be improved if more attention is paid to similarity between training, assessment and daily life tasks performed with the AT.

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Declaration of Competing Interest

None.

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