Intermanual Transfer in Training

with an Upper-Limb Myoelectric Prosthesis Simulator

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ABSTRACT

Background. Intermanual transfer might improve prosthetic handling and acceptance if used in training soon after an amputation.

Objective. To determine whether intermanual transfer effects can be detected after training with a myoelectric upper-limb prosthesis simulator.

Design. Randomized controlled trial.

Participants. Able-bodied right-handed (N=48, 23 men, 25 women), randomly assigned to experimental and control groups.

Intervention. The experimental group performed a training program on five days using the prosthesis simulator. To determine the improvement in skill, a test was administered before, immediately after, and six days after training. The control group only performed the tests. Training was performed with the ‘unaffected’ arm, and tests were performed with the ‘affected’ arm, (simulating the amputated limb). Half of the participants were tested with the dominant arm and half with the non-dominant arm.

Measurements. Initiation time, the time from starting signal until start of the movement; movement time, the time from the beginning of the movement until completion of the task; and force control, the maximal applied force on a deformable object.

Results. The movement time decreased significantly more in the experimental group (F_{2,92}= 7.42, P=.001, \eta_G^2= .028). This is indicative of faster handling of the prosthesis. No statistically significant differences were found between groups with regards to initiation time and force control. We did not find a difference in intermanual transfer between the dominant and non-dominant arm.

Limitations. The training utilized able-bodied subjects in a laboratory setting and only focused on transradial amputations.

Conclusions. Intermanual transfer was present in the ‘affected’ arm after training the ‘unaffected’ arm with a myoelectric prosthesis simulator and this did not depend on laterality. This effect might improve rehabilitation of patients with an upper-limb amputation.

LIST OF ABBREVIATIONS

ANOVA Analysis of Variance
PAULA Prosthetists’ Assistant for Upper Limb Architecture
SHAP Southampton Hand Assessment Procedure
INTRODUCTION

The rate of use of prosthetic devices in persons with an upper extremity amputation is low, as about 30% of the potential users reject the devices.\textsuperscript{1-4} This high incidence of rejection is not only due to technical limitations, but can also be attributed to a limitation in prosthesis skills following the injury. It has been suggested that if users started earlier with their prosthesis training this would lead to improvement in the skill of prosthetic handling and a greater acceptance of the device.\textsuperscript{6, 9, 26, 27} However, it is often not feasible to start prosthetic training immediately after the amputation because of the time needed for wound healing, as well as time for fabrication and fitting of the prosthesis. Training immediately after amputation might be facilitated if intermanual transfer was used. This is already found to be useful in body-powered prosthetic use, but it has never previously been tested with myoelectric prostheses.\textsuperscript{18} Intermanual transfer\textsuperscript{13, 28-30} implies that motor skills learned at one side of the body transfer to the other side. For patients with an amputation this means that training with the ‘unaffected’ arm enhances the motor skills of the amputated arm.\textsuperscript{18}

Intermanual transfer can be understood from the generalized motor program framework as put forth by Schmidt.\textsuperscript{31, 32} After training a motor skill, a generalized motor program, defining a class of movements, is stored in memory. This motor program is used for a specific class of movements (e.g. writing a signature) and contains relative variables, such as the relative timing and relative force. These variables specify the proportional time a submovement lasts within the total movement time, and the proportional force a submovement exerts in comparison to the total force, respectively. One example of a relative variable is the percentage of time taken to write one letter within a signature. These relative variables remain invariant over the same class of movements. In addition, for each movement produced within a class of movements, the absolute timing and absolute force are adapted to the task demands. When performing a task such as writing, the absolute variables change, including speed, amplitude and muscles used. These parameters are not part of the generalized motor program. Within this framework, the relative parameters (i.e. the parameters that remain invariant within a class of movements) can be transferred to the contralateral hand. Parameters specifying absolute time and absolute force that are tuned to the specifics of each individual movement are harder to transfer. The transfer of relative timing has been demonstrated in the literature, which supports the generalized motor program theory, whereas absolute force was harder to transfer.\textsuperscript{16, 33-35}
Weeks et al.\textsuperscript{18} showed learning effects of intermanual transfer in body-powered prosthetic use. In a body-powered prosthesis, the prosthetic hand is connected to a harness around the contralateral shoulder. Hand opening is directly controlled through movement of the shoulders and trunk. The current paper examined intermanual transfer in myoelectric upper-limb prostheses. Hand opening and closing in a myoelectric prosthesis is controlled by activation of forearm muscles that turn on and off the electric motors. Such prostheses are indirectly controlled by activation of the muscles, contrary to the direct control of body-powered prostheses. The delay in indirect control is what makes it unnatural. Moreover, proprioceptive control of the opening of the hand is not available and therefore the grip aperture is only perceivable through vision. This indirect control of myoelectric prostheses might affect learning how to handle these prostheses,\textsuperscript{36} and might influence the effect of intermanual transfer.

The number of people that have recently had an upper-limb transradial amputation and who will for the first time be provided with a myoelectric prosthesis is not large enough for a statistically relevant study. To establish the effects of intermanual transfer we made use of able-bodied participants using a transradial prosthesis simulator (Fig. 1).\textsuperscript{37, 38} This simulator can be attached to an unaffected arm. In myoelectric control the wrist extensors and flexors control hand opening producing grasping profiles that are similar for simulators and real prostheses.\textsuperscript{39} Using a prosthesis simulator to train one arm (i.e., the ‘unaffected’ arm) while testing the other arm (i.e., the ‘affected’ arm), allowed us to study intermanual transfer of myoelectric prosthesis training in able-bodied subjects.

The aim of this research was to reveal whether intermanual transfer effects could be detected after training with a myoelectric prosthesis simulator. Based on the generalized motor program theory we

![Figure 1. (A) The myoelectric simulator attached to an unaffected arm (B) the inside of the Velcro sleeve showing the electrodes.](image-url)
hypothesized that when participants train with the prosthesis at one side of the body:

1) The initiation time will become shorter at the untrained side;
2) The movement time will become faster at the untrained side;
3) The force control will not improve at the untrained side.

Laterality was tested because it is important for the purposes of rehabilitation whether laterality affects intermanual transfer. Furthermore, it is assumed in literature that new and complex tasks favour the transfer from the dominant to the non-dominant arm. Therefore we hypothesized:

4) That there would be a greater improvement in movement time when the dominant hand is trained and the non-dominant hand is tested than the other way around.

**METHODS**

**Design overview**

The experimental group started with a pretest (day 1) to establish skills of the subjects’ ‘affected’ arm using the simulator. They then practiced for five days with the opposite ‘unaffected’ arm (day 1-5). Subsequently, participants from the experimental group performed a post-test (day 5) and retention test (day 11) using the simulator on the ‘affected’ arm. The control group executed the pretest, post-test and retention test on the same days, using only the ‘affected’ arm and received no training. The pretest, post-test and retention test consisted of five test tasks all executed three times in random order.

**Setting and Participants**

Forty-eight right-handed and able-bodied volunteers participated (23 men, 25 women; mean age 24.6 y). All participants were free of known neurologic or upper extremity musculoskeletal problems, had normal or corrected to normal sight and had no earlier experience with the prosthesis simulator. Hand dominance was determined by self-report.

All participants signed an informed consent document before participation. The study was approved by the local ethics committee (NL35268.042.11). After completion of the experiment, participants received a gift voucher.
The myoelectric prosthesis simulator (OIM Orthopedie, Haren, The Netherlands) used for the experiments consisted of a myoelectric hand, the MyoHand VariPlus Speed (Otto Bock, Duderstadt, Austria), attached to an open cast in which the hand was placed (see Fig. 1). The cast extended into a splint along the forearm, and was adjustable in length. The splint could be attached to the arm using a Velcro sleeve. The hand was controlled by changes in electrical activity related to muscle contraction, detected by two electrodes that were placed on the muscle bellies of the in the forearm. The prosthetic hand had proportional speed control (15-300 mm/s) and proportional grip force control (0-±100 N).

**Randomization and Interventions**

Participants were randomly assigned to one of two groups, the experimental and the control group. For half of the participants the dominant side was tested as the “affected” limb, and for half the non-dominant side was tested as the affected limb.

All test and training sessions started with a standard procedure to fit the simulator. After palpation of wrist extensor and flexor muscles, the locations were marked with a permanent marker and the electrodes were placed on those locations. To determine the correct location and sensitivity of the electrodes, Otto Bock’s PAULA software, (Otto Bock, Duderstadt, Austria) was used in conjunction with a MyoBoy (757M11 Myoboy; 13E200 MyoBock Electrodes; Otto Bock, Duderstadt, Austria) with USB connection to a PC. With PAULA software the muscular signals were presented on the screen. To set the sensitivity of the electrodes, the amplified signal had to exceed a threshold of 1.5 V (high signal) sustained for two seconds. A maximum of five contractions was allowed to minimize training effects. The maximum speed of the hand was set to the default setting of six (double channel control, fast open and slower closing). After the simulator was fitted, the participant was positioned in front of the table with the elbow 90 degrees flexed. Verbal instruction on the execution of the tasks was given.

**Pretest, post-test and retention test**

Five test tasks were administered in the pretests, post-tests and retention tests; three functional tasks and two force control tasks. The test tasks took no more than 15 minutes. During all tasks, participants sat in front of a task board (60x60 cm) showing the start and end positions of the objects.
The functional tasks were based on the three different ways a prosthesis is used in daily life\textsuperscript{42}; direct grasping, indirect grasping and fixating. For the ‘mug task’, the participant had to pick up a mug by the handle and place it 25 cm above the table on a shelf.\textsuperscript{38} In the ‘jar lid task’, a jar was picked up by the unaffected hand and had to be passed to the prosthetic hand, the lid then had to be removed by turning it with the unaffected hand.\textsuperscript{38} While in the ‘pen case task’, a pencil case was held with the prosthetic hand in the starting position, after which the zipper was opened with the unaffected hand. E-Prime (Psychology Software Distribution, York, UK) was used to measure initiation time and movement time of these tasks, recorded in milliseconds. Before each trial, a computer screen on the left side of the participant showed which task had to be executed. A keyboard was positioned next to the task board at the side of the arm that was tested. Participants were instructed to execute all tasks as rapidly and accurately as possible. The space bar was used to time the tasks, when the subject removed the hand the movement was started, after executing the task the participant pressed the space bar again. The initiation time was taken as the time between the auditory tone and the release of the space bar. The movement time was defined as the time between the release of the space bar and pressing the space bar after completing the task.

In the force control tasks, a deformable object\textsuperscript{39} had to be picked up and put on a shelf 30 cm above the table; subjects were instructed to compress the object as little as possible. The deformable objects consisted of two plates (6 cm x 3.5 cm x 9 cm) with a spring in between (Fig. 2). In one condition the spring provided a constant force of 5.31 N/mm and in the other condition the spring provided a constant force of 0.17 N/mm. The maximum deformation was measured by reading a scale attached to the plates.

Figure 2. Deformable object with the measurement scale.
Training sessions
During the training sessions, participants in the experimental group trained using the tasks from SHAP.43 SHAP evaluates functionality of hand prostheses and consists of 26 tasks; twelve abstract object tasks and 14 activities of daily life tasks. Each training session with the SHAP was approximately 30 minutes in length, with each participant performing one session on days 1 and 5, and two sessions on days 2-4.

Statistical Analyses
The means of the initiation times, movement times and object deformations for the three trials in each test were calculated. The results of the pretests of the experimental and control group were compared using a repeated-measures ANOVA with task (mug, jar lid, and pen case) as a within-subject factor and training group (experimental and control) as between-subject factor, to examine whether the two groups were different.

Hypothesis 1: Initiation time
To compare the initiation times of the experimental and control groups on the different tasks, z-scores were used. The z-scores were calculated for each task and were used for further analysis. A repeated-measures ANOVA on initiation time was conducted on the functional tasks, with test (pretest, posttest, and retention test), and task (mug, jar lid, and pen case) as within-subject factors, and training group (experimental and control) as between-subject factor.

Hypotheses 2 and 4: Movement time and hand dominance
For the movement times the z-scores were calculated for each task. A repeated-measures ANOVA on movement time was conducted on the functional tasks, with test (pretest, post-test, and retention test) and task (mug, jar lid, and pen case) as within-subject factors, and training group (experimental and control) and hand dominance (dominant and non-dominant) as between-subject factors.

Hypothesis 3: Force control
Repeated-measures ANOVA were conducted on the maximal deformation in the force control tests with test (pretest, post-test and retention test) and task (strong and light spring) as within-subject factors, and training group (experimental and control) as a between-subject factor.
When sphericity was violated, the degrees of freedom were adjusted with the Greenhouse-Geisser correction. In the analyses, a significance criterion of 0.05 was used, and post-hoc tests on main effects used a Bonferroni correction. The effect sizes of the significant effects were calculated according to the $\eta_G^2$ as described by Bakeman\textsuperscript{44} and Olejnik\textsuperscript{45} and interpreted according to Cohen’s recommendation\textsuperscript{46} of 0.02 for a small effect, 0.13 for a medium effect and 0.26 for a large effect. Only the effects with an effect size greater than 0.02 are reported in the results.

**RESULTS**

**Pretest**

The ANOVAs on the pretest for initiation time, movement time and force control data showed no differences between groups. Mean initiation and movement times are presented in Table 1.

**Functional tasks**

*Hypothesis 1: Initiation time*

The ANOVA on the initiation times showed that these times were comparable for both groups over all tests ($F_{2,92}= 2.39$, $P=.097$, $\eta_G^2= .005$). A significant main effect for test ($F_{1.449,66.674}= 15.74$, $P=.000$, $\eta_G^2= .038$) indicated that the initiation times decreased over the three tests. Post-hoc analysis showed that the pretest differed from the post-test ($P<.001$) and from the retention test ($P<.001$). No other significant main effects or interactions were found.

*Hypothesis 2: Movement time*

The ANOVA on movement time showed that the effect of primary interest in this study, the interaction between test and group, was significant ($F_{2,88}---= 7.77$, $P=.001$, $\eta_G^2= .047$). Three unpaired t-tests, using a Bonferroni correction, revealed that the groups differed significantly from each other in the retention test ($t(46) = -2.55$, $P=.014$), but not in pretest nor in posttest. The decrease in movement time over sessions was greater for the experimental group than for the control group (Fig. 3). Large differences among tests ($F_{1.344, 59.156}= 182.98$, $P=.000$, $\eta_G^2= .512$) were found. Post-hoc analysis indicated that all tests differed significantly from each other (all $P$'s < .001), revealing that participants had were faster in the post-test and the retention test.
Table 1. Means (CI) for initiation times (IT, ms) and movement times (MT, ms) for the functional tasks per test.

<table>
<thead>
<tr>
<th></th>
<th>Experimental group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mug</td>
<td>Pen case</td>
</tr>
<tr>
<td>IT</td>
<td>Pretest</td>
<td>379 (353-405)</td>
</tr>
<tr>
<td></td>
<td>Posttest</td>
<td>352 (329-375)</td>
</tr>
<tr>
<td></td>
<td>Retention test</td>
<td>336 (323-349)</td>
</tr>
<tr>
<td>MT</td>
<td>Pretest</td>
<td>7478 (6893-8062)</td>
</tr>
<tr>
<td></td>
<td>Posttest</td>
<td>4715 (4420-5010)</td>
</tr>
<tr>
<td></td>
<td>Retention test</td>
<td>4180 (3932-4429)</td>
</tr>
</tbody>
</table>

Table 2. Mean scores (CI) for the deformation (mm) of the force control tasks.

<table>
<thead>
<tr>
<th></th>
<th>Experimental group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light spring</td>
<td>Strong spring</td>
</tr>
<tr>
<td></td>
<td>Pretest</td>
<td>14.49 (12.86-16.11)</td>
</tr>
<tr>
<td></td>
<td>Posttest</td>
<td>11.55 (9.94-13.18)</td>
</tr>
<tr>
<td></td>
<td>Retention test</td>
<td>11.02 (9.47-12.58)</td>
</tr>
</tbody>
</table>
Force control tasks

**Hypothesis 3: Force control**
The ANOVA on force control indicated that improvement in the two groups did not differ. The ANOVA showed differences among tests ($F_{2,90} = 11.28, P=.000, \eta^2_G = .044$). Post-hoc analysis showed that the pretest differed from the post-test ($P<.001$) and the retention test ($P=.006$), respectively (Tab. 2). Since there were no other main effects or interactions, improvement in the two groups did not differ.

**Hypothesis 4: Hand dominance**
In the ANOVA on movement times no interaction effect between dominance and session was found. A main effect of hand dominance for movement time ($F_{1,44} = 10.20, P=.003, \eta^2_G = .14$) was found. Accordingly, the tasks executed with the dominant hand were performed faster (dominant 629 and non-dominant 541 ms). Moreover,
an interaction effect between task and test hand was found \( (F_{2,88} = 10.51, P = .000, \eta^2 = .05) \). Three unpaired t-tests, using Bonferroni correction, revealed faster performance with the dominant hand in the mug \( (t(46) = -3.54, P = .001) \) and pen case tasks \( (t(46) = -3.99, P = .000) \). The jar lid task was performed equally fast for both hands.

**Role of the Funding Source**

This study was supported by ZonMW. The sponsor had no role in any aspect of the study design, conduct, analysis, interpretation or reporting.

**DISCUSSION**

In this study the intermanual transfer effects after training with an upper-limb myoelectric prosthesis simulator were tested according to the generalized motor program. We expected that initiation times would decrease significantly after training, but we had to reject this hypothesis. It is generally assumed that the execution of new tasks affects initiation time, because this requires more planning. In our study, test tasks differed from training tasks, which might explain why we did not find any transfer effects of initiation time. Our second hypothesis, a significantly faster movement time in the experimental group, was accepted. These findings indicate that after applying intermanual transfer training prosthesis handling generalized to tasks other than the ones used for training. This is in spite of the fact that the pre-movement planning of these tasks (indicated by initiation time) did not improve. The control of the force, the third hypothesis, did not show significant differences in improvement. The results from the second and third hypotheses were in agreement with theoretical considerations. The analyses on hand dominance for the movement time, the fourth hypothesis, showed that the intermanual transfer effect was symmetrical in myoelectric prosthetic training. Most authors find laterality effects favoring one direction, implying that the dominant side benefits more from training the non-dominant side, and occasionally vice versa. Several reasons are suggested for the laterality, such as asymmetric neural architecture, movement parameters or nature of the task, and complexity or novelty of the task. Contrary to the findings of Teixeira and Weeks, a difference in laterality was not found in the performance of a complex task. Hence, our expectations were not confirmed.
A weakness of this study is that we tested a specific situation. First, we did not test whether transfer effects were present in persons with an amputation, because only able-bodied participants using a prosthesis simulator were included. However, because persons with an amputation are generally healthy and because the kinematic performances observed in simulators are comparable to performance with real prosthetic devices\textsuperscript{39}, we expect that the intermanual transfer effects will be reproducible in persons with an amputation. Next, we tried to resemble clinical practice as much as possible but we realize we have not investigated a real rehabilitation setting. In our experiment, the training period was shorter in duration than the typical rehabilitation protocol, the number of tasks used was limited and we only focused specifically on transradial amputations. Nevertheless, intermanual transfer is found to be effector independent\textsuperscript{34, 52, 53} and thus not based on a certain task or on certain muscles. It is the effect of intermanual transfer that gives the results, independent of the task, the level of the amputation or the muscles used.

Results of the retention test (Figure 3), which was applied after six days without training, showed that both groups performed faster in the retention test than in the post test. Note that the experimental group performed the tasks 13\% faster than the control group. The difference between the post test and retention test in the experimental group has been found quite often in literature.\textsuperscript{54} It is commonly assumed that these changes are caused by motor memory consolidation, and thus the performances at retention are generally considered to be a better indicator of motor learning.\textsuperscript{54} While the improvement in the control group likely reflects a certain degree of the learning of how to use the prosthesis, the difference between the groups reveals the added value of the intermanual transfer due resulting from training.

The additional length and weight of the prosthesis simulator alters the inertia of the limb and with this the intersegmental dynamics.\textsuperscript{55} However, prosthesis users are able to adapt to such perturbations.\textsuperscript{56} Because in our experiment the simulator was used on both arms, the changes in intersegmental dynamics were equal on both sides and no new adaptations needed to be learned by the participants. However, in the case of an actual prosthesis being used in a real life setting (following an amputation), adaptations to the properties of the prosthesis and the accompanying intersegmental dynamics will have to be considered. Presumably these changes only require adjustments to the absolute force of the learned motor program. Hence, we expect
that with actual prosthesis users the intermanual transfer effects will also be found despite the overlength of the simulators used in training.

The generalized motor program theory, which was taken as the starting point in the design of this study, is not the only perspective explaining the intermanual transfer effects. For instance, the dynamical systems perspective on motor coordination explains intermanual transfer from the idea that abstract coordination dynamics, containing the stable coordination modes, are instigated through learning a task. When performing the same task with a different effector these coordination dynamics interact with the dynamics of this new effector and the available information to create the actual behavior. This paradigm has been developed mainly for rhythmic tasks, but can also be applied to discrete movements, much like the ones used in our experiment. For instance, Zaal et al. suggested that hand opening and hand closing are two stable attractors of which the stability is regulated by time-to-contact the object. Although Zaal et al. developed this for natural prehension, this notion should also work for prosthetic grasping, because opening and closing of the hand are also stable behaviors. From this perspective, one could argue that an abstract coordination dynamics, containing the stable states of hand opening and hand closing, are set up during training. These abstract dynamics will interact with the specific dynamics of the untrained effector in the post-test, transferring the learned skill to the untrained effector. Hence, our findings on movement time and force control are explicable within this framework. However, intermanual transfer has not been studied very thoroughly within the dynamic systems approach, making it difficult to formulate specific hypotheses, such as concerning transfer of force. It is for this reason that makes the generalized motor program theory more applicable.

The design of our study resembled rehabilitation practice more than in other studies on intermanual transfer. For instance, training was extended over several days, the tasks used were complex and included activities of daily life tasks, and the test and training tasks differed from each other in order to examine generalizability of the training. Pereira et al. also studied intermanual transfer in complex tasks over several days but found only small improvements. This was presumably due to the fact that they examined training of general hand function in healthy people, which is already a well developed skill. Weeks et al. studied prosthetic training with a body-powered prosthesis, though only with one day of training and using the same test and training tasks. They found improvements of initiation time and movement time,
implying improvement in both the planning and performance of the tasks. Our study was the first to reveal intermanual transfer effects in myoelectric prostheses. We demonstrated improvement in movement times of new tasks, showing that intermanual transfer influenced overall handling of the prosthesis. Thus, we succeeded in detecting intermanual transfer effects despite a more complicated and extended experimental set-up in comparison to others.18, 59

The main argument to include intermanual transfer in rehabilitation is that by using a simulator, training of people with an upper-limb amputation can start earlier, which may lead to increased use of upper-limb prostheses.8 Furthermore, due to intermanual transfer effects, persons with an amputation might start using their prosthesis at a higher performance level. This is likely to increase motivation and, with that, the use and acceptance of the prosthesis.6, 9, 26, 27 To apply intermanual transfer in the clinic it is necessary for clinicians to obtain a prosthesis simulator, though clinicians would not require further training. Although we realize that fitting a real prosthesis directly after the amputation is preferable, in many patients this is not feasible due to healing wounds and accompanying edema or because of the costs of temporary prostheses. In these cases, applying intermanual transfer effects might be a valuable addition to current rehabilitation practice.

Further research should focus on different aspects of the training to improve the intermanual transfer effects that we have found. Future research that we are currently planning examines the timing and duration as well as the specific tasks that optimize the effect of intermanual transfer. Furthermore, insight in the kinematic performances should increase understanding of the underlying processes. With these future studies the clinical relevance of our findings for patients with upper-limb amputation might become clearer.

**CONCLUSION**

Intermanual transfer effects were present after training with a myoelectric prosthesis simulator in healthy participants. It was found that: 1) the initiation time did not show intermanual transfer effects, presumably because of the differences in training tasks and test tasks; 2) The movement time showed intermanual transfer effects; while 3) the force control did not. Finally, 4) no laterality effects were found. These findings suggest that intermanual transfer might be of clinical relevance for persons with an upper limb amputation, because intermanual transfer training would enable patients to start prosthetic training shortly after the amputation.
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