Restoring Natural Forearm Rotation in Transradial Osseointegrated Amputees

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***Abstract*—Osseointegrated transradial prostheses have the potential to preserve the natural range of wrist rotation, which improves the performance of activities of daily living and reduces compensatory movements that potentially lead to secondary health problems over time. This is possible by enabling the radius and the ulna bone to move with respect to each other, restoring the functionality of the original distal-radioulnar joint. In this paper we report on psychophysics tests performed on an osseointegrated transradial amputee with the aim to understand the extent of mobility of the implants that is required to preserve natural forearm rotation. Based on these experiments, we designed and developed an attachment device between the implants and the hand prosthesis that serves as an artificial distal radio-ulnar joint. This device was fitted on an osseointegrated transradial amputee and its functionality assessed by means of the Southampton Hand Assessment Procedure (SHAP) and the Minnesota Manual Dexterity test (MMDT). We found that axial rotation of the implants is required to preserve forearm rotation, to distribute loads equally over the two implants (60% radius – 40% ulna), and to enable loading of the implants without unpleasant feelings for the patient. Higher function was recorded when our attachment device enabled forearm rotation: SHAP from 61 to 71, MMDT from 258s to 231s. Natural forearm rotation can be successfully restored in transradial amputees by using osseointegration and our novel mechanical attachment to the hand prosthesis.**

***Index Terms*— artificial limbs, prosthesis fitting; osseointegration; transradial amputation; forearm rotation.**

I. Introduction

Upper limb amputations have a considerable impact on the ability of individuals to perform activities of the daily living. Such amputations are mostly caused by trauma, and to a smaller extent by cancer or infection [1], contrary to lower limb amputations which are mostly caused by vascular diseases. Even though upper limb amputations are less than a fifth of the total number of amputations, the prevalence of this type of this amputation is high due to the younger age of the patients [2]. Among upper limb amputations, approximately half are below the elbow [1],[3]. A way to partially restore functions and appearance of the amputated limb is by the use of a prosthesis connected to the residual limb by means of a suspension system. This is the part of the prosthesis that is in direct contact with the user, and although is often overlooked, it is one of the most important components of a prosthetic system. The most common attachment system is the self-suspended socket, which is designed to conform over the stump and often exploits the epicondyles of the humerus to suspend the prosthesis (namely *supracondylar suspension*). A socket often causes problems such as excessive sweating, skin irritation, unsatisfactory mechanical stability in the connection, and reduced range of movement of adjacent joints leading to high rates of rejection of the prosthesis [4],[5]. By anchoring a prosthetic device directly to the skeleton, these issues can be avoided and the quality of life can be improved considerably [6],[7]. Direct skeletal attachment can be safely realized via osseointegration [8], [9], a principle that has been used in dental implants, bone anchored hearing aids and maxillofacial replacements since 1965, and for limb prostheses since 1990 [9],[10].

Mid to long transradial amputations often preserve enough musculature to allow for forearm rotation [11]. This movement (namely pronation and supination of the hand, prono-supination) is used extensively in daily life in a large variety of tasks [12],[13]. In amputees, the remaining range of pronation/supination is a linear function of the residual forearm length [14]. As an example, an amputee with 2/3 of intact forearm has approximately 90° of forearm rotation still available [15]. A socket prevents the rotation of the forearm by mechanically blocking this motion, reducing the benefits of natural prono-supination. The lack of forearm rotation forces the individuals to compensate for it by changing the motions of their arms and body [16],[17]. Such compensatory movements often result in residual limb pain and secondary musculoskeletal complaints and overuse syndromes over time [18],[19].

Osseointegration releases external restrictions allowing the radius to rotate over the ulna, thus enabling natural and proprioceptive-rich control of forearm rotation. This could allow transradial amputees to perform activities of daily living (ADL) more efficiently and with limited or no compensatory movements. However, enabling natural forearm rotation by

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I. Boni and J. Millenaar are with Integrum AB, Gothenburg, Sweden (email: irene.boni@integrum.se; jason.millenaar@integrum.se).

M. Controzzi is with The Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy. (e-mail: marco.controzzi@santannapisa.it).

M. Ortiz-Catalan is with Biomechatronics and Neurorehabilitation Laboratory, Department of Electrical Engineering, Chalmers University of Technology, and Integrum AB, both in Gothenburg, Sweden (email: maxo@chalmers.se).

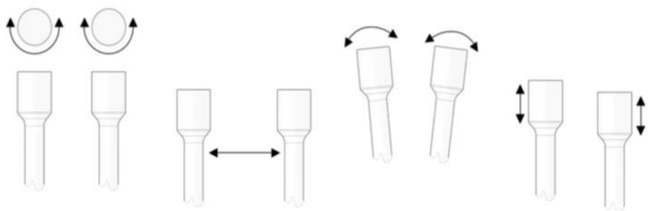

Figure 1 - Motions of the two abutments observed in osseointegrated transradial amputees during forearm rotation. From the left to the right: Axial rotation, interosseous variable distance, angular deviations and distal translations.

means of an osseointegrated implant presents several challenges, such as the complex kinematics of forearm rotation over the length of the forearm. The ulna forms a hinge joint with the elbow, and the radius moves over it describing an asymmetric trajectory during pronation and supination [20],[21]. The curvature of both bones creates variability in positioning of the bones with respect to each other depending on forearm angle and level of amputation. This results in a complex rotational axis which is still subject of discussion [22]. However, in the case of a transradial amputation, the lack of the wrist articulation and interosseous membrane disrupts the kinematical architecture of the forearm, making it difficult to identify which motions need to be accommodated by a prosthetic attachment device that could also serve as an artificial distal radio-ulnar joint. In patients with bone-anchored implants, the motion of these bones during forearm rotation can be observed directly by looking at the percutaneous portions of the implants (as shown in Figure 1), which are called abutments. By observing these movements, we noticed that axial rotation has a considerable contribution and might be the most important degree of freedom to allow for wrist rotation. Published literature supports this notion in able-bodies [23],[24],[25]. However, constraining the remaining degrees of freedom could limit the range of motion and produce discomfort during operation. In this work, we investigated our hypothesis that axial rotation of the ulna and radius bones is enough to restore near-natural wrist rotation.

An additional challenge to restore wrist rotation in patients with bone-anchored prostheses is the load distribution between the implants in the ulna and radius bones. H. Shaaban *et al.* have shown that the axial force transmitted through these two bones in cadavers with intact limbs is related to the applied axial load [26]. In addition, they found that the load distribution between the two bones significantly changes for different angles of forearm rotation. On average, the radius supports ~68% of the axial load [26]-[27]. To the best of our knowledge, there is no previous work investigating the load distribution in amputees with osseointegrated implants. In the case of osseointegrated implants, one must consider that an even load distribution between the two implants would prevent excessive loads on only one implant, and therefore reduce the chance of a mechanical failure in said implant. Current attachment devices for osseointegrated transradial amputation (TRA) realizes this even load distribution by locking the two implants together, which eliminates the ability to naturally rotate the forearm.

In this article, we report on a novel artificial distal radio-ulnar joint and attachment device sought to enable forearm rotation in TRA patients with bone-anchored implants. To address this objective, we first analyzed the movements of the unconstrained abutments. Then we set up different tests aimed to understand which movements of the implants need to be accommodated in order to preserve forearm rotation, to promote an equal distribution of load between the bones, and to realize these aforementioned goals without generating discomfort for the amputee. Finally, the benefits enabled by the preserved forearm rotation were assessed trough the Southampton Hand Assessment Procedure (SHAP) and the Minnesota Manual Dexterity test (MMDT) in a TRA patient with bone-anchored implants using an attachment device designed based on these guidelines.

II. Material and Methods

A. Participant

In the present study, we enrolled a 37 year old male with a below-elbow amputation (right handed), long stump (residual radius length > 110mm), and who has been using an osseointegrated implant system since 2011 without mechanical complications (OPRA Implant System, Integrum AB, Sweden). Both implants had a diameter of 8 mm, and the percutaneous portion of the abutments was approximately 30 mm long. This study was approved by the Regional Ethical Review Board in Gothenburg, Sweden, and written inform consent was obtained from the patient prior to experimentation.

B. Attachment configurations

In order to investigate which movements of the abutments need to be accommodated to preserve forearm rotation, we developed a set-up that allows constraining the abutments in two different configurations. In one experimental condition (*Configuration 1* –C1–) all motions observed in osseointegrated transradial amputees when the abutments are unconstrained and completely free to move (Figure 1) were allowed to a limited

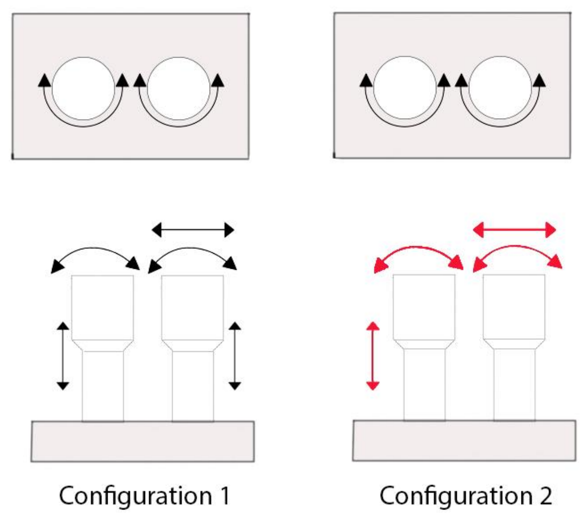

Figure 2 – Motions of the abutments allowed by the set-up in the two different experimental conditions. Left - Top and front view of the set-up related to Configuration 1 (C1), in which the abutments are allowed to move in all directions to some degree. Right - Top and front view of the set-up related to Configuration 2 (C2), in which the abutments are only allowed to rotate axially; the red arrows show the movements that can be adjusted before being locked.

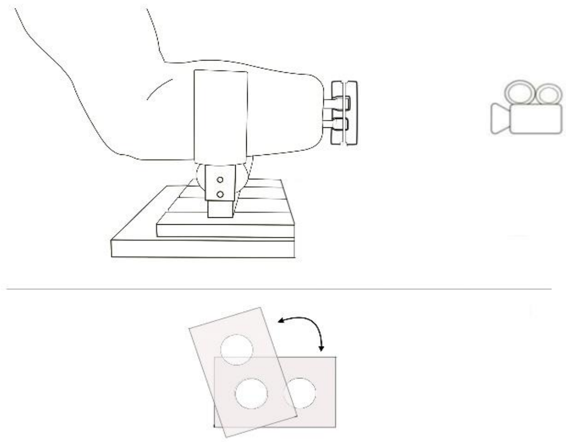

Figure 3 – Experimental setup of the experiment 1. The patient was asked to rest his forearm on a support and then to rotate the forearm maximizing the range of motion while a camera was used to record the motion of the set-up. The maximal range of motion was then measured by analysing the video footage.

degree (Figure 2). In particular, both abutments were able to rotate axially and were allowed slight angular and distal deviations. Furthermore, the radius was allowed to move in a track in order to account for the change in distance between the abutments (i.e. interosseous distance).

For the second condition the aim was to discover which of these movements are minimally necessary in order to preserve forearm rotation. Initially only axial rotation of the abutments was admitted (Figure 2), locking all other movements. Within this configuration the interosseous distance, the angular deviation, and the distal offset can be adjusted to the subject before being locked (indicated in red in Figure 2). Preliminary tests with this set-up indicated that this configuration was already sufficient to preserve the motion, which is why this configuration was chosen as the second configuration (*Configuration 2* –C2–) for further investigation.

C. *Experimental procedures*

1) *Experiment 1: Preserved range of motion*

The maximal range of motion of the forearm was measured and compared between both configurations (C1 and C2), as well as with unconstrained abutments (CC). For each configuration, the measurement of the range of motion followed these steps: the patient was asked to rest his forearm on a support that ensured a stable positioning in a comfortable way; the abutments were constrained according to the specific configuration; a camera (Nikon, model Coolpix L120) was placed in front of the forearm in a fixed location; the patient was asked to rotate the forearm 5 times maximizing the range of motion (Figure 3). For each repetition, two still images were taken from video footage corresponding to the full pronation and the full supination position of the forearm. These pictures were overlapped and then aligned digitally using Adobe Photoshop (Adobe, USA). The angle between 2 lines joining the abutments was taken as reference for measuring the maximal range of motion.

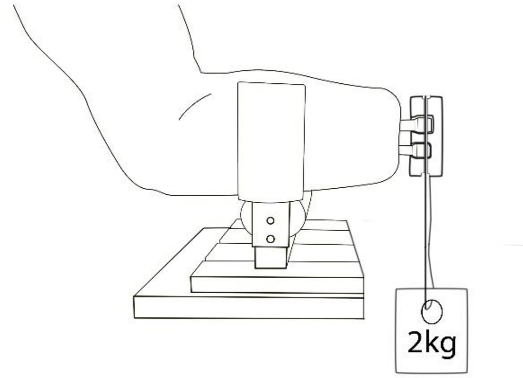

Figure 4 – Experimental setup of the experiment 2. The patient was asked to rest his forearm on a support. The weights were applied directly to the set-up connecting the two abutments.

2) *Experiment 2: Static Loading*

The aim of the second experiment was to assess the different configurations in terms of comfort when the implants are loaded by means of the developed set-up. In a preliminary test the patient was asked to carry a weight of 2 kg in both configurations and to report in case of unpleasant feelings. *Configuration 1* was excluded from a further investigation regarding the loading since the subject reported an uncomfortable sensation, as if there was a pulling force on the implant. Subsequently, a psychophysics test was performed to evaluate the impact of loading the abutments on the experience of the patient in *Configuration 2*. The experiment was repeated varying the following three parameters: *forearm angle* (neutral position, fully pronate, and fully supinate), *weight* (2, 2.5 and 3 kg), and the *interosseous distance* (18 and 21mm). The different interosseous distances were selected according to what the patient indicated to be comfortable. Starting from the interosseous distance, which corresponds to the distance in the patient's previous attachment device used in daily life (18mm), the two abutments were moved and locked at different interosseous distances slightly farther and closer as allowed by the patient's anatomy. The experimental protocol comprises of the following steps: the abutments were constrained and the patient was asked to rest his forearm on a support that ensured a stable and comfortable position; then he was asked to rotate the forearm in the experimental condition requested by the trial, and the abutments were loaded once the given position was reached (Figure 4). The subject was blinded, carried the weight for three seconds, and once the weight was removed, he was asked to rate his experience by scoring unpleasantness with a number ranging from 0 to 5. For each trial the angle, weight and interosseous distance were randomly varied and each condition was repeated 6 times, for a total of 108 trials.

3) *Experiment 3: Prono-supination*

The third experiment was performed to investigate if only axial rotation of the abutments is sufficient to preserve forearm rotation, and to evaluate the impact of changes in interosseous distance between the abutments on the experience of the patient during an unloaded dynamic rotation of the forearm. This experiment was restricted to *Configuration 2* since this configuration allows keeping the interosseous distance constant in each condition. The experimental protocol was designed based on *Single Case Experimental Design* (SCED) guidelines

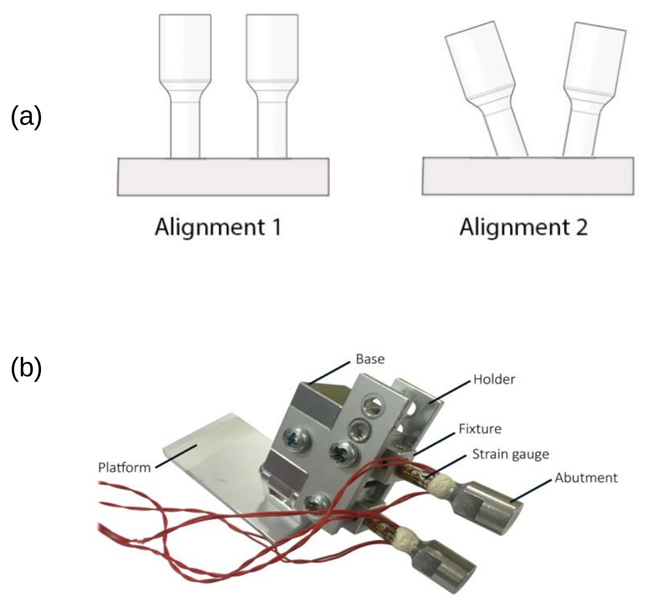

Figure 5 – (a) Schematic of abutment alignments simulating different patient fitting. Alignment 1 corresponds to parallel abutments and Alignment 2 corresponds to diverging abutments; (b) Test rig with the abutments instrumented using strain gauges.

[28],[29],[31]. In particular, we opted for the most common experimental procedure used in single case research: ABAB design (i.e. "withdrawal design"). It consists of repeated measurements taken for a single subject under two different alternating conditions in four phases with several measurements in each phase [32],[33]. In this experiment, phase A corresponds to the interosseous distance that is used in the patient's conventional attachment device (18mm) and phase B to a slightly greater interosseous distance (21mm). For each phase, the patient was asked to rotate his forearm from full pronation to full supination 5 times. The cycle ABAB was repeated 3 times. In each trial, the subject was blinded and after each trial he was asked to rate his experience by scoring unpleasantness with a number ranging from 0 to 5.

4) Experiment 4: Load distribution

The load distribution in static condition over the two implants was compared between the two configurations for different *forearm angles* (vertical, diagonal and horizontal) and abutment alignments simulating the condition of different patients (i.e. parallel – *Alignment 1* – or diverging – *Alignment 2*) (Figure 5a). A test rig was used for this experiment (Figure 5b). It comprises of two fixtures in which the abutments could be fixated using set screws, holders keeping the fixtures in place, a base to which these holders were attached, and a platform that was used to attach the rig to a table. The abutments were instrumented using strain gauges (HBM, type LY11-06/120) in order to retrieve the load distribution in the abutments. The abutments were then loaded with 5 kg in the two experimental conditions (i.e. *Configuration 1* and *Configuration 2*). The abutments were able to rotate within the fixtures when the set screws were loosened, so that the gauges were kept in the correct positioning during the whole experiment. The angle of

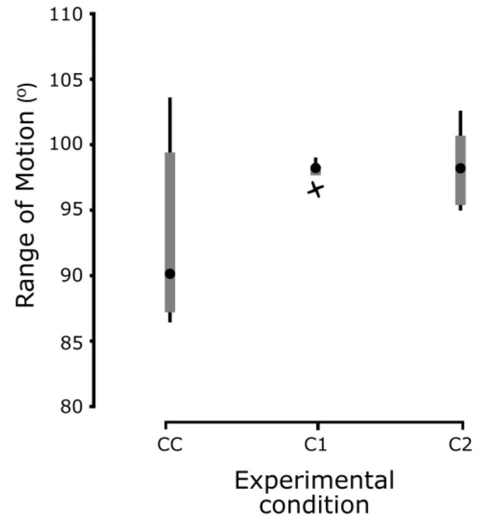

Figure 6 – Maximal range of motion of the forearm for different configurations of the abutments. From left to right: unconstrained abutments (CC), abutments connected to the *Configuration 1* of the set-up (C1), abutments connected to the *Configuration 2* of the set-up (C2).

the rest rig and the alignment of the abutments were fixated at the beginning of each trial.

5) Experiment 5: SHAP and MMDT

The ability of executing ADLs and the hand-arm dexterity with and without the possibility to exploit the natural forearm rotation was evaluated using the SHAP [34] and the turning task within the MMDT [35]. The attachment devices used in the experiments were the patient's previous attachment device (which constrains the forearm rotation) and a novel attachment device specifically designed to enable forearm rotation. The SHAP is divided in two parts: in the first one, composed of 12 tasks, the subject grasps and manipulates abstract objects (cylinders, tabs, spheres, etc.); in the second part he was required to perform 14 ADLs, such as turning a door handle, picking up coins, moving containers, etc. [34],[36]. The SHAP is a time-based protocol and the subject is required to complete the tasks as quickly as possible. The execution times are used to calculate the global Index of Function (IOF) and six partial IOFs related to the six main grasp types involved in the test.

The MMDT focuses on measuring manual dexterity [37]. In this test the subject is asked to pick up a number of small disks which are black on one side and red on the other, with one hand and turn them over with that same hand, then take them with the other hand, and finally place them in a dot raster with this second hand row by row. There are four rows in total. The dexterity of the subject is measured based on the time required to accomplish the test.

III. Results

A. Experiment 1: Preserved range of motion

The maximal range of motion was evaluated and compared between the two configurations and unconstrained abutments, see Video 1. Results are shown in Figure 6. The mean values (averaged on 5 repetitions) of the range of motion are: 93.1°±7.36 with unconstrained abutments, 97.9°±0.89 and 98.1°±3.13 for *Configuration 1* and *2*, respectively.

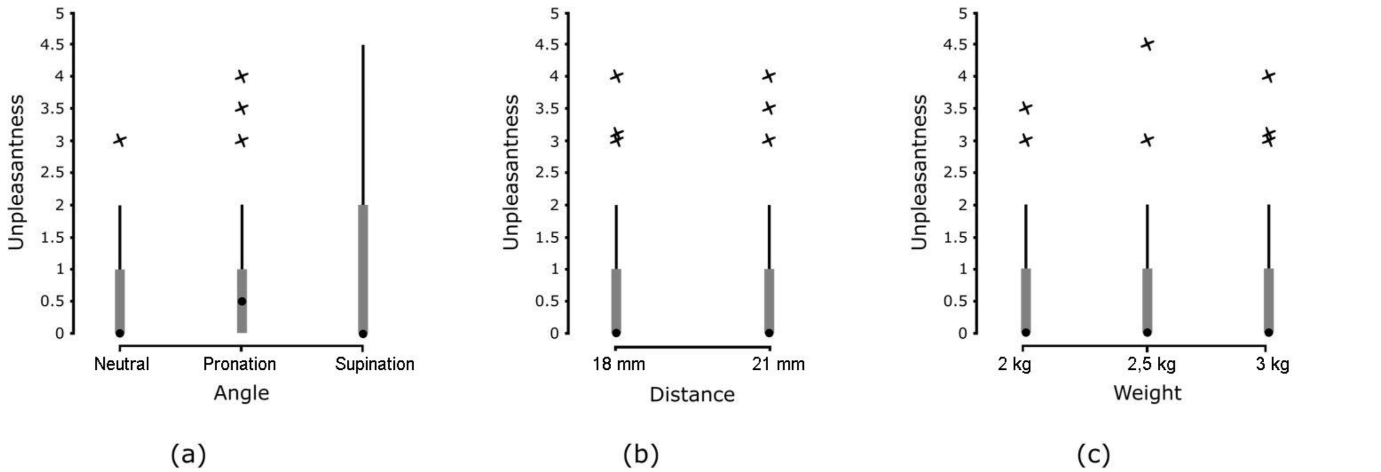

Figure 7 – Impact of the forearm angle (a), interosseous distance (b) and weight (c) on the experience of the patient using the attachment device in *Configuration 2*. The unpleasantness is rated using a 0 to 5 point scale. For each condition the test was repeated 6 times.

B. *Experiment 2: Static Loading*

When the patient was asked to bear 2 kg using *Configuration 1*, an uncomfortable feeling in the area of the implants was reported. For this reason, no further testing regarding load carrying was performed using this configuration. A total of 108 scores (3 *weights* X 3 *forearm angles* X 2 *interosseous distances* X 6 *repetitions*) were obtained using *Configuration 2*. Overall, the uncomfortable feeling reported in *Configuration 1* was not experienced by the subject in *Configuration 2* under any experimental condition. The impact of *forearm angle* was analyzed by splitting the data into 3 groups depending on the forearm angle (Figure 7a). The Kruskal-Wallis test revealed no statistically significant difference among the different angles (p=0.21). In order to analyze the impact of *interosseous distance*, data were split in two groups depending on the distance (Figure 7b). Data were analyzed statistically using the Kruskal-Wallis test. No significant difference between the two interosseous distances was found (p=0.4). Finally, data were split into 3 groups depending on the *weight* (Figure 7c), in order to analyze the impact of the weight carried on the experience of the patient. No significant difference was found between different weights (p=0.9).

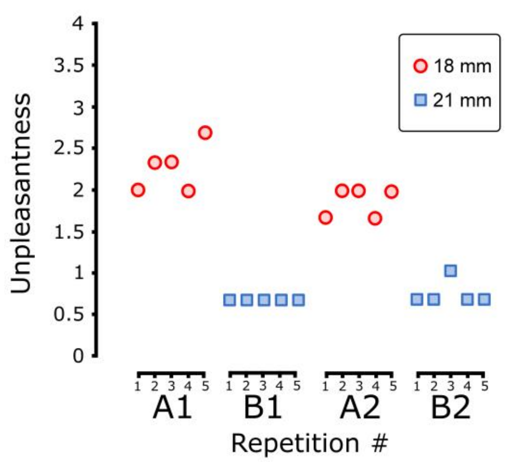

Figure 8 – Average values obtained from the prono-supination psychophysics test using the attachment device in *Configuration 2*. D1 and D2 correspond the interosseous distance of 18 mm and 21 mm respectively.

C. *Experiment 3: Prono-supination*

The cycle ABAB was repeated three times. The values shown in Figure 8 are the average values of the three repetitions.

The average value of the unpleasantness score for an interosseous distance of 18 mm was 2.1±0.64 versus an average score of 0.6±0.79 for 21 mm. The Kruskal-Wallis test resulted in the rejection of the null hypothesis: a statistically significant difference between the two interosseous distances was found (p<< 0.05).

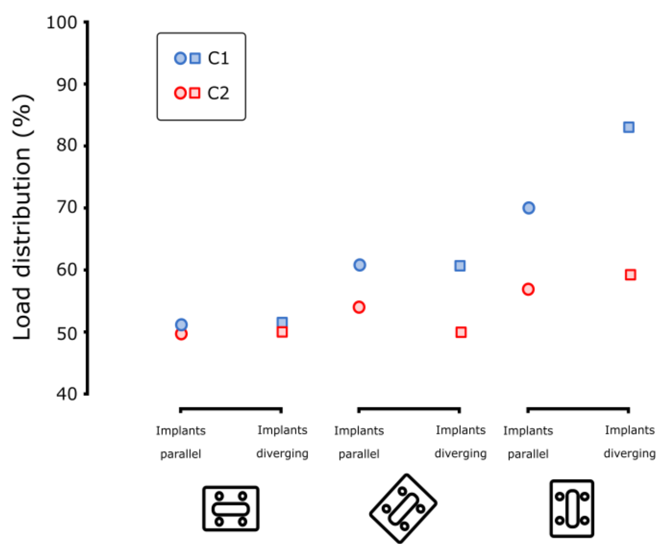

Figure 9 – Percentage of the load distribution in the radius for the two configurations (*Configuration 1* –C1– coloured in blue, and *Configuration 2* C1– coloured in red) of the setup for different simulated forearm angles and implant alignments (parallel implants represented using circle, and diverging implants plotted as square).

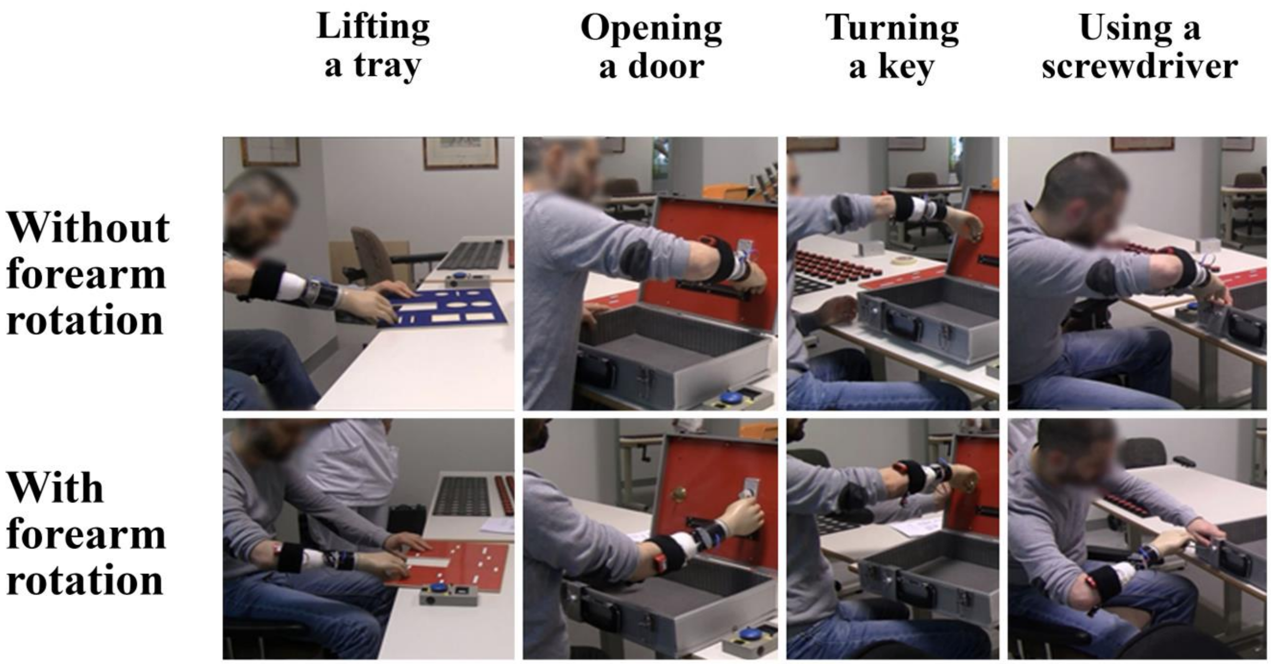

Figure 10 – Postures of the patient during task performance with the ability to perform forearm rotation (bottom row) and without it (upper row).

D. *Experiment 4: Load distribution*

Figure 9 shows the distribution of the load for the two configurations of the setup for different simulated forearm angles and abutment alignments. The loads measured in the abutment that corresponds to the implant in the radius of a TRA patient are plotted as a percentage of the total load that was measured. *Configuration 1* distributed the loads less evenly over the abutments than *Configuration 2*. This was the case for both implant alignments, but more so in the diverging position, in which the biggest difference in load was observed (83% on the radius for *Configuration 1*). In both configurations, the loads were distributed more evenly when the test rig was positioned more horizontally. In *Configuration 2*, the load on the radius ranged between 50% and 60%.

E. *Experiment 5: SHAP and MMDT*

For the "Abstract Objects" section of the SHAP, 5 out of 10 tasks were performed faster with forearm rotation enabled and in 6 out of the 10 tasks compensation for forearm rotation was observed when forearm rotation was locked. In the "Daily Living" section of the test, 7 out of 14 tasks were performed faster with the attachment device enabling forearm rotation. For half of the tasks (7 out of 14) forearm rotation or shoulder movement replacing forearm rotation was observed. Figure 10 shows a number of instances where the ability to perform forearm rotation changed the execution of the task: for 4 tasks the same moment is captured with forearm rotation (bottom images) and without it (upper images). The Index of Function score improved from 61 to 71 by using natural forearm rotation.

Within the Minnesota Manual Dexterity test, each run was performed faster with the attachment device enabling forearm rotation (see Video 1), with a mean time of 231 s with the ability of rotation versus 258 s without it.

IV. Discussion

A. *Experiment 1: Preserved range of motion*

The range of motion is larger and more repeatable (the data is less scattered) when the abutments are constrained in either of the two configurations compared to condition with unconstrained abutments. These results suggest that the attachment device may play an important role in restoring the kinematics of the wrist articulation, and thus increasing the stability of two bones. Indeed, the sound forearm consists of two bones connected at the proximal end and at the distal end. As result of the amputation, the bones are not connected distally because of the lack of the wrist. This means that the stability that the healthy wrist articulation provides is absent in transradial amputees and a prosthetic attachment device could replace this functionality.

B. *Experiment 2: Loading*

Configuration 1, when loaded with a minimum weight during the preliminary test, resulted in unpleasant sensations for the patient. This indicates that an attachment device designed to accommodate all motions observed in the unconstrained abutments during forearm rotation is not optimal. The results of the psychophysics test using *Configuration 2* yielded no statistically significant difference between the selected parameters (i.e. *interosseous distance*, *forearm angle*, and *weight*), meaning that in static load scenarios, these variables do not impact the comfort of the patient. However, several factors should be taken into account before general conclusions can be drawn. Firstly, these tests were performed with a single patient. Repeating this experiment with a larger number of osseointegrated TRA patients would give insight into how the experience of carrying loads varies for different patients. Secondly, the expression of unpleasantness varied over the course of the experiment. Even though the subject was asked to score unpleasantness in the same way each time, he expressed difficulties in doing it because the nature of the sensation changed at times. The sensation was sometimes described as fatigue, while in other instances a trembling or slight pressure was expressed. The difference in perceived unpleasantness owing to the different quality of sensations have had an impact on the scores and should be considered in a further investigation.

C. *Experiment 3: Prono-Supination*

We found that accommodation of only the axial rotation of the abutments (*Configuration 2*) preserves forearm rotation. Furthermore, results of the prono-supination test show that there is a statistically significant difference between two interosseous distances when the subject rotated the forearm dynamically. This suggests that configuring the correct interosseous distance is an important factor in the patient's experience of any future attachment device to a prosthesis that would allow natural forearm rotation.

D. *Experiment 4: Load distribution*

The result of the load distribution experiment indicates that an equal distribution of the load can be achieved if the abutments are constrained to allow only axial rotation (*Configuration 2*). This could explain why the subject reported an unpleasant sensation when carrying a weight in *Configuration 1*. In particular, in this configuration the abutments were attached asymmetrically, as one of them could move in a track while the other was fixed, replicating the motions observed in the unconstrained abutments. Due to this asymmetry, the load distribution between the two implants became uneven and this may have led to the unpleasant sensations. On the contrary, *Configuration 2* promotes an even load distribution between the implants, which enhances the experience of the patient. Different *forearm angles* were replicated by rotating the test rig. The impact of the different angles on the load distribution is intuitive: when the abutments are positioned horizontally, there are no differences in bending or shear stress between the two abutments and the measured load is equally divided between the two. Positioning the rig more vertically causes differences in the aforementioned stresses, the magnitudes of which depend on the exact positioning of the abutments. However, *Configuration 2* was shown to be less sensitive in this respect, showing a small variability of the load distribution between the implants for different angles of the forearm. This behavior is preferred since it reduces the chance of over stressing one implant in a particular posture, and it provides uniform comfort in different postures. The *alignment of the abutments* within the test rig seems to have an impact on the load distribution between them. The reason for this effect could be that the direction of the resultant force in each abutment becomes different when the angulation of the implant changes. This effect should be studied more intensively by testing different abutment alignments before general conclusions can be drawn.

A considerable simplification of the present test is the simulation of the forearm with a rigid metal interface. In an amputee, loads will be transferred from the abutments to fixtures which are osseointegrated into the ulna and radius bones. These bones have some flexibility themselves and are surrounded by soft tissues. This complex structure will undoubtedly change the stiffness of the implant system, resulting in a different load distribution. However, the correspondence between the observed results of this test and the patient's experience supports the validity of these measurements.

E. *Experiment 5: SHAP and MMDT*

The results reported during the execution of the SHAP and MMDT clearly indicate that overall performance is enhanced by enabling natural forearm rotation. This is not surprising and it is coherent with the literature investigating the importance of the wrist dexterity in upper limb prostheses [38]. In addition to the outcome measures obtained, a number of interesting observations were made during the execution of the SHAP. The most noticeable, and perhaps most important one, was a reduction of compensatory movements at the shoulder when forearm rotation was enabled. Different postures for the same task with and without forearm rotation are shown in Figure 10. The patient had not used pronation and supination with his missing limb for over a decade but having the chance to use it immediately changed the use of the prosthesis in several tasks. It is worthwhile to note that not all tasks which involved forearm rotation were performed faster when using the new attachment device. This may be due to different factors. Since the SHAP replicates ADLs and the patient had not used this motion for a decade, he may have felt more confident when performing the movement compensating with the shoulder. It stands to reason that for these tasks a longer practice may promote the use of the forearm rotation, and in turn increase the efficiency of the execution.

Another statement that can be made after having done this test is that the addition of pronation and supination alone is not always enough to drastically change the way the prosthesis is used. Not all tasks that were expected to change when natural forearm rotation was possible actually did. In order to naturally perform some of the more dexterous tasks (such as pouring a cup of water or cutting food), additional degrees of freedom in the wrist would be needed (e.g. wrist flexion/extension and radio-ulnar deviation) [38]. Because of these limitations, these tasks were performed nearly identically in the two configurations and often requiring compensatory shoulder movements.

At times combining pronation and supination with opening and closing of the prosthesis resulted in difficulties with prosthetic control by using surface EMG, and this has also affected the outcome measures of the tests. One likely explanation is that electrical activity from a pronator or supinator muscle got occasionally picked up by the surface electrodes and was mistaken for the intention of opening or closing the hand. In addition, the surface electrodes are placed on fixed locations and when forearm rotation occurred, the original alignment of the electrodes with respect to the residual forearm muscles changed, reducing the controllability of the prosthesis.

The MMDT mainly showed the need of degrees of freedom in addition to pronation and supination, specifically wrist flexion/extension. Even with the possibility to perform forearm rotation, in order to be able to grasp the disks, the prosthetic hand has to be positioned slightly vertically, which would have been achieved in a healthy limb by means of the wrist flexion movement. It was subjectively observed by the experimenters that shoulder movements were exploited by the subject in order to compensate for the lack of the wrist flexion. When the disk was picked-up and lifted, the required adduction of the shoulder already resulted in the disk being turned over. This means that the freedom to pronate or supinate was almost redundant for this task.

V. Conclusion

Accommodating for all degrees of freedom observed in osseointegrated transradial amputees preserves their natural range of forearm rotation. However, this configuration provides an uncomfortable feeling to the patient when the implants are loaded. Although the kinematics of forearm rotation are complex, the tests performed in a single amputee subject indicate that forearm rotation in osseointegrated amputees can be preserved by only allowing the implants to rotate around their individual axes, provided that the initial interosseous distance and abutment angular deviation are adjusted appropriately. Furthermore, this configuration does not provide any uncomfortable feeling to the patient during both loading in static postures and in dynamic motions of the forearm. In a static load bearing situation with the implants constrained in this configuration, no significant change in patient experience was observed with respect to forearm angle or interosseous distance. However, even during unloaded pronation and supination, the interosseous distance seems to have an impact on patient comfort. Regarding load distribution, preserving only axial rotation of the abutments resulted in an equally distributed load over the implants. Not loading one of the implants considerably more than the other has two benefits: it seems to increase patient comfort and it prevents one implant failing mechanically sooner than the other, increasing the lifetime of the whole implant system. Finally, the preservation of natural forearm rotation seems to be worthwhile: it adds a natural, proprioceptive-rich degree of freedom that allows for more natural and efficient use of the prosthesis during the execution of activities of the daily living.

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