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RESEARCH ARTICLE

Categorization and Evaluation Methods for Control Strategies of Bilateral Tasks in Arm Prosthetics

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ABSTRACT Controlling multi-joint prostheses intuitively and effortlessly has been a research topic since the appearance of the first electric elbow prostheses. Researchers mainly focused on single handed tasks, however in daily life these are mostly executed with the healthy hand and the prosthetic arms only become relevant for two-handed manipulations. Thus, a new approach is presented in this paper addressing bilateral tasks. A taxonomy for bilateral tasks is elaborated in order to categorize and prioritize bilateral manipulations involving a prosthetic arm. Five different key figures for rating bilateral movements are introduced and used to form two quality criteria, which allow evaluation and comparison of different control strategies. Based on the proposed taxonomy and quality criteria, a generalized benchmark test environment is developed with five different evaluation scenarios and realized in virtual reality in an exemplary manner. Furthermore, a new controller-agent strategy, greatly facilitating the usage of prosthetic arms, is presented. The effectiveness of the criteria for evaluation of different control strategies is demonstrated with healthy subjects. With this evaluation concept, we provide the community a means to explore and compare controlling methods and inputs, facilitating the progress and development of new strategies.

INDEX TERMS Bilateral manipulations, upper limb prosthetics, virtual reality.

I. INTRODUCTION

Many daily activities like working with devices and machinery or manipulating different objects are designed for two-handed operations. Thus, the loss of an arm is rendering a person dependent on the help of others in everyday life. Prostheses are meant to support the individuals in their daily tasks and allow them to be reintegrated into their social environment [1]. Despite the years of research and commercial exploration of the domain, the available devices are not yet able to replace the missing body parts in their entirety. A lot of progress has been made regarding to hand prostheses, but above-elbow amputees are still limited to the same systems used decades ago. Research is mainly focusing on unilateral actions that are performed with arm and hand prostheses, which is not expedient and does not correlate with prosthesis wearer's needs, as multiple studies have shown: The most desired improvements are related to bilateral actions, like eating with fork and knife, buttoning up shirts or generally getting dressed [1], [2]. Unilateral actions performed with the prosthesis are only accounting for a fraction of its usage [3]. Losing a limb above the elbow is highly restricting the affected person. Simple tasks like opening doors or water bottles are burdensome and commercially available systems are only of limited help due to the complex controls of these multi-joint systems, which is one reason for prostheses' high rejection rates [4]. A lot of training, patience and concentration is needed to master the controls of these prostheses,

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but this does not always increases the acceptance [5]. This leads the amputated person to a biased unilateral behavior, where every action that can be executed with one hand is performed with the healthy extremity. In [6], amputees and non-amputees were observed throughout their day and their usage of respective arm workload was analyzed. From a nearly 50-50 distribution between left and right for non-amputees, amputees shifted their workload to over 79% onto their healthy arm. The many available features of the prostheses are neglected due to the complicated operation modes [7]. Depending on the amputation level, there are up to five powered joints that need to be controlled, besides the prosthetic hand. These joints should replace shoulder abduction and adduction, shoulder rotation, ante- and retroversion, elbow flexion and extensions as well as wrist rotation. Controlling each joint individually can quickly overwhelm the wearer and thus lead to rejection of the prostheses.

This creates a necessity for alternative controls of prosthetic arms. As controlling each joint separately is neither user-friendly nor desired by the patients [7], a paradigm shift in research goals is required towards a more user-oriented target control strategy. To improve controls in a way to facilitate the ease-of-operation by the user instead of maximizing the diversity of movements, a focus on bilateral actions is proposed. In order to be able to compare different control strategies, a systematic evaluation method is needed. This includes a structured way to describe bilateral actions as well as a quality criterion based on which the effectiveness of a control strategy can be quantified. Additionally, a testing environment is developed, to evaluate the here presented quality criteria.

II. OBJECTIVES

Bilateral actions include tasks that are concluded with two hands or arms. This comprises e.g., catching a ball with two hands. In opposition to this, unilateral actions are performed with one limb only, as e.g., grasping a cup. This differentiation is especially important with regard to prosthetic devices for upper limbs, as bilateral actions are no longer possible without the help of others or the prosthesis. There is a clear bias to execute unilateral actions with the healthy limb, and thus the unimportance of executing unilateral tasks with the prosthesis [6]. As such, the main benefit is the ability to perform bilateral actions. Due to the earlier mentioned focus on unilateral actions in research, many fundamental findings are missing in relation to bilateral manipulations. A unified categorization as well as a rating and evaluation strategy for these movements and often similar processes are redundantly defined [8], [9], but not systematically described which hinders a comparison of results as the testing environments differ. To facilitate research on bilateral actions, a taxonomy is proposed and can be used to categorize movement sequences systematically. Based on this taxonomy, a comparison between different control schemes is conceptualized. For bilateral tasks, the effectiveness, effort, speed, and success rate are monitored and compared with each strategy. Besides a two-handed bilateral manipulation with healthy subjects and a conventional and commercially available control scheme, a controller-agent control strategy with a focus on bilateral tasks is presented in Section IV. Five key figures are presented which quantify different aspects of an action sequence and are used to formulate a new quality criterion. This criterion allows to evaluate and compare the execution of the bilateral tasks, and thus compare the control strategies and allow a statement on the necessity for a bilateral controller-agent system. Additionally, a virtual reality (VR) environment is developed and presented, which provides a setting to gather the necessary metrics to calculate the quality criterion and assess the different strategies. The effectiveness of the newly described control strategy is demonstrated inside the virtual reality setting for a non-amputee and presented in Section VIII and to be analyzed further in an upcoming study including amputees and non-amputees.

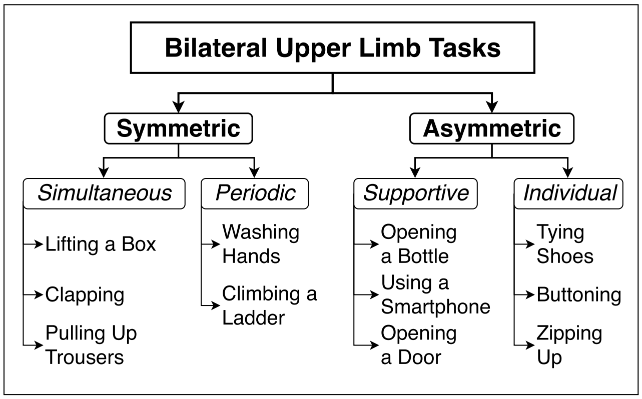


FIGURE 1. Taxonomy for bilateral actions.

III. TAXONOMY FOR BILATERAL ACTIONS

A taxonomy is a systematic grouping into hierarchical classes or categories. In relation to bilateral actions this becomes particularly relevant to unambiguously describe movements and actions. By grouping together activities, more general assumptions and statements can be made in addition to an easier evaluation of grouped tasks. The goal is to conceive a unified and consistent categorization of bilateral actions for upper limbs to classify daily activities. Based on this classification, it is possible to discern which movement patterns are more frequent in everyday life and thus shift the focus on these categories, which could be part of future work. A taxonomy also helps in discovering dependencies on different aspects such as user input, environmental information or goals, and as such allows to implement a task-based control strategy instead of a complex multi-action strategy which again overwhelms the user. A fundamental taxonomy is designed to describe bilateral actions. It is displayed in Fig. 1 and distinguishes between symmetric and asymmetric movements.

If both hands or arms are performing identical or similar movements, they are to be classified as symmetric movements. Furthermore, simultaneous, and periodic actions are considered separately. The former are movements which occur at the same time by both extremities, e.g., clapping hands or pulling up a trouser. The latter include all alternating and repetitive motions like washing hands.

The group of asymmetric movements comprises supportive and individual movements. Individual movements, such as tying shoes, consist of two fundamentally different actions, which complement each other and can only work together. Both extremities are executing distinguishable and independent motions, but their common action relies on their cooperation. In contrast, supportive actions always consist of a primary and a secondary task, whereas the secondary always assists the primary one. E.g., opening a bottle requires one hand to hold it, which is the secondary task, while the other hand is manipulating the cap to open it up.

IV. CONTROLLER-AGENT CONTROL STRATEGY

The conventional sequential control makes use of multiple input signals to control each joint of the prosthesis individually. Usually, two myoelectric inputs are used to control the whole arm, each signal moves the selected joint in a given direction. By producing a trigger signal, that is a distinct contraction of one or more muscles, the amputee can switch between the joints and thus control the whole arm prosthesis sequentially [10]. This method of controlling the prosthetic device is tedious for the user. The patient must plan the joint's end-position in the kinematic chain first, then sequentially move each in order to achieve the desired end effector position. The high cognitive load combined with the physical effort to produce the trigger signals leads to exhausting controls [7]. By inspecting the taxonomy in Fig. 1, it becomes evident that most bilateral tasks can be accomplished either by completely mirroring the movements of the other hand, or by partially mirroring them to reach a final position in which the prosthesis is locked. A new control strategy has been conceptualized and is developed at Vincent Systems GmbH. The healthy arm is hereafter denominated controller, and the prosthetic device is the agent. The controller signalizes the prosthetic device to start following its movements. Taking into account their positional discrepancy, the agent follows and mirrors the controller's movements until the controller indicates otherwise. Making use of this controller-agent scheme, each of the symmetric simultaneous movements can be accomplished without further input from the wearer. By mirroring the movements of the healthy arm, these can be accomplished faster and without effort, as to be shown. This novel method for controlling a prosthesis facilitates the daily bilateral activities. Asymmetric supportive movements can also easily be performed. E.g., opening a bottle involves two tasks, grabbing the bottle and screwing of the cap. Thus, by making use of the controller-agent strategy, the user would, in a first step, start the mirror movement and then use his healthy arm to grab the bottle. The agent follows the mirrored path until grabbing the bottle as well. In a second step, the prosthetic device can be locked with an external signal, such as a quick muscle contraction. The healthy arm,

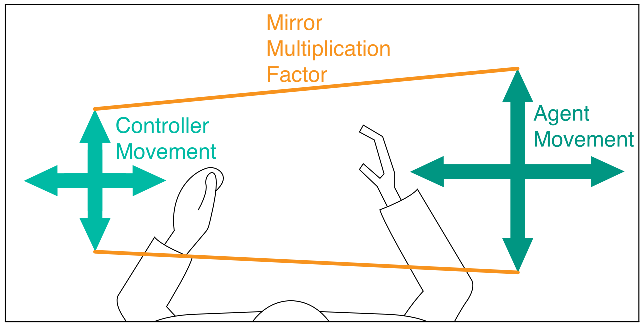


FIGURE 2. Visualization of the mirror multiplication factor.

no longer having the controller role, can be used freely to screw open the cap. This strategy tremendously decreases the cognitive load on the user and speeds up the sequence compared to the alternative control strategies, as the user does not need to think about moving each joint individually. As the main input signals come from the healthy arm, the patient has much more control as compared to conventional control strategies, which rely on the input of the residual limb. This control strategy can be implemented in two ways, either as a direct mirroring as stated above, or as a remote control. A multiplication factor can be introduced as displayed in Fig. 2. The actual controller's translation is to be amplified by a given factor and thus increasing the agent's range of motion. In case of the bottle opening activity, the controller no longer needs to grab the bottle, but performs the movement in a smaller scale, moving the arm and hand only a fraction of the way, whereas the prosthetic device moves all the way to the bottle. As such, the fatigue of the healthy arm can be reduced and the controlling is not as obvious to the outer world, which can lead to increase in acceptance of the system. It depends on the situation the user is in, whether direct mirroring or remote controlling the prosthesis is more convenient and the user can change between the modes at runtime. In order to implement such a strategy to control a prosthesis, different sensory input could be used. Camera systems, tracking the healthy arm, could be used either as standalone system, or in combination with accelerometer and gyroscope sensors. Additionally, EMG signals could be used to have even more control input.

V. QUALITY CRITERION

Five key figures are being presented hereafter, which constitute the quality criterion. These numerical values allow to calculate a total score of an action, which then can either be compared to a benchmark movement of a given control strategy and the resulting criterion value, or with other executions by different subjects with different strategies.

A. DURATION OF ACTIONS

An important figure to assess the usefulness of a control strategy in daily life is the duration of an action. The task specific and user individual duration leads to:

$$F_1 = t_u \tag{1}$$

with u designating the user. (1) is defined as key figure F_1. A two-handed execution of a bilateral task by a healthy subject is considered as benchmark movement and represents the optimal duration for a given task and subject.

B. TRAJECTORY OF ACTIONS

Besides the duration, the trajectory taken is also important. An object can move in a swift manner, but on a sub-optimal path. Thus, a manually predefined trajectory for each task represents the optimal path and is displayed to the user inside the virtual reality environment. The discrepancy between the taken path and the optimal one is being used to calculate key figure F_2:

$$F_2 = \int_0^{t_e} |\mathbf{r_{OP}}(\mathbf{r_c}(t)) - \mathbf{r_c}(t)| dt \tag{2}$$

with t_e being the endpoint in time when the target is reached as elapsed seconds since start, $\mathbf{r_c}(t)$ the actual position at timestamp t as coordinates in meters based on the starting position and $\mathbf{r_{OP}}(\mathbf{r_c}(t))$ the closest point on the optimal trajectory path to the current position at t.

C. PRECISION OF ACTIONS

Each defined bilateral task has a target zone which needs to be reached. A target position and rotation are defined, and the deviation from this orientation is being used to calculate a score given the following equation:

$$F_3 = \frac{1}{k_{\text{distance}} d_{\text{target}} + k_{\text{rotation}} r_{\text{target}}} \tag{3}$$

with d_{target} being the distance between the object and the target position and r_{target} the rotation offset between the two. The weights $k_{\text{distance}} = 10$ and $k_{\text{rotation}} = 1/10$ showed to be a good balance between distance and rotation offset. The achieved score is designated as key figure F_3.

D. SUCCESS RATE

Each collision of a target object can be monitored and tracked. Based on the velocity of an impact, one can examine whether an object is being dropped or bumped into an obstacle. This leads to key figure F_4, the success rate on how collision free an action was executed

$$F_4 = \sum_c \|\mathbf{i_c}\| \tag{4}$$

where c is the collision index and $\mathbf{i_c}$ the impact vector of the given collision in $\text{kg} \cdot \text{m/s}$. The impact vector represents the total collision impulse of all contact points involved in the collision. It is the integral of the collision forces at each contact point over the duration of the collision [11], and its magnitude thus can be interpreted as the heaviness of the collision.

E. USER ASSESSMENT

Given the fact, that a prosthetic device needs to be used throughout every day, another key figure is the user's perception of the different control strategies. This does comprise the mental and physical effort it takes to control and use the prosthesis, the perceived ease of use and its effectiveness, the proneness to errors as well as how intuitive the controls are. This figure F_5 is measured by conducting a survey on the subjects after using each control strategy in the virtual reality environment. The survey and the numbered questions referenced hereafter can be found in the supplements. Questions 1 to 5 collect basic background information on the subject, and are not part of the key figure calculations, but they can be used in future evaluations. Rating scales for mental and physical effort are presented to the users, with scales from 1 to 5 where 1 is "Not Exhausting" and 5 is "Very Exhausting". The same applies to the proneness to errors, the intuitiveness, and a subjective value from 1 to 5 on how hard it was to accomplish the given task. After all control strategies have been used, the user is asked to compare the learning curve, ease of use and intuitiveness of sequential and mirrored controls. To account for the effort due to the fact that the simulation happens in VR, the results for the two-handed controls (question 7 to 11) with healthy subjects is collected as well, even though it should represent the most natural and easy-to-use control strategy. The responses are then used to calculate F_5

$$F_5 = \sum_q w_q Q_q \tag{5}$$

Question 12 to 16 are respective to the sequential control and 17 to 21 are related to the controller-agent strategy.

Based on the performance indicators F1-F5, quality criteria can be formulated. The key figures must be normalized by a reference value in order to have a unified scale and thus allow a qualitative statement on the grade of a bilateral action for a given control strategy. The reference movement is defined as the bilateral execution of a task for non-disabled subjects and thus a value of one on the resulting scale would represent an optimal outcome equal to the movement of an non-disabled subject. As such, it can be distinguished between a user-individual and a group-based normalization. The first for intra-user, symbolized by Q_{ui}, and the second for inter-user, symbolized by $Q_{\lambda i}$, comparisons. For amputees, the mean value of each intra-user normalization factor can be used.

Quality Criterion 1: The intra-user quality rating for each control strategy Q_{ui} is given by

$$Q_{ui} = \sum_{n=1}^{5} (\upsilon_{un} F_{uni}) \tag{6}$$

with u indicating the user, i as index for the control strategy, υ_{un} as weight for the task n, F_{uni} as the key figure for the given user and task. In order to balance the weight of each figure given their different value ranges (from 0 to over 1200), the task weight υ_{un} is calculated by dividing the sum of each task for the given key figure by the sum of F_4 over all control strategies. F_4 was chosen, as its value for two-handed control is expected to equal 0, and thus cannot be further normalized without distorting the values. The quality rating for the reference movement is $Q_{u\text{ref}}$ and together this forms the first quality criterion:

The user-individual viability, robustness and speed of a control strategy is determined by Q_{ui}. If the normalized quality criterion value $Q_{ui}Q_{u\text{ref}}^{-1}$ is larger than one, it suggest a less qualitative control strategy, whereas smaller values would imply controls superior to normal two-handed interactions.
A more generalized value is the inter-user quality rating $Q_{\lambda i}$.

Quality Criterion 2: This rating compares not only user individual results, but gives a broader rating for each control strategy, considering the performance of all subjects, including those of amputees. It is formulated as

$$Q_{\lambda i} = \frac{1}{m}\sum_{u=1}^{m} Q_{ui} \tag{7}$$

where i is the index of the control strategy, m denotes the total number of participants and u the users. The second criterion, together with the rating for the reference movement $Q_{\lambda\text{ref}}$, can be formulated:

The overall and user independent viability, robustness and speed of a control strategy is determined by $Q_{\lambda i}$. Larger values than one for $Q_{\lambda i}Q_{\lambda\text{ref}}^{-1}$ suggest a less qualitative control strategy when compared to the chosen reference strategy, whereas smaller values would imply controls superior to the chosen reference.
With these two criteria it is possible to evaluate whether a control strategy is useful only for individual cases, or if it can be successfully utilized in a general manner.

VI. BILATERAL BENCHMARK TASKS

In order to evaluate different strategies, a benchmark test is needed. This test comprises tasks, which represent daily bilateral activities and focus on elementary movements and actions with two hands and arms. Each of the five tasks presented hereafter has a different difficulty which is to be solved by the subject. These tasks are generally applicable and can be used as benchmark in either a real world setting or in a virtual reality environment with any kind of control strategy and prosthesis. The exemplary execution procedure in VR for each task is detailed in Figure 3. After the control strategy and the task to be completed have been selected, the VR scenario is loaded. Based on the selected control strategy, the corresponding sensory input is activated and the used to control the virtual prosthesis. The user can then start the task, while the simulation starts the necessary measurements to be able to calculate the key figures. The duration, the trajectory and all occurring collisions are recorded. Once the task is completed, the final position as well as the objects orientation are saved, and the key figures can be calculated.

A. TASK ONE: MOVING A BOX FROM LEFT TO RIGHT WITHOUT HEIGHT VARIATION

The first task is to move a box from a table on the left side, to a table on the right side of the user as shown in Fig. 4 (a). This task requires the subject to position the joints of the prosthetic arm once, to grab the box at hip level, and then rotate the upper body to get the box to the target zone. This task needs

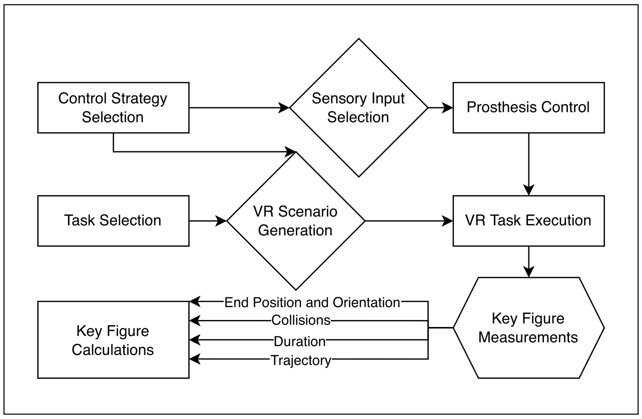


FIGURE 3. Diagram of VR execution flow for each task.

little effort and nearly no re-positioning of the joints while having the box grabbed.

B. TASK TWO: LIFTING A BOX FROM THE FLOOR AND PLACING IT ON A TABLE

To lift a box from the floor and place it on a table is the second task. It requires joint movements to be able to reach the target box as well as while lifting it to avoid hitting the table. This requires already a basic amount of re-positioning while moving the upper arm but does not involve switching joints yet. It is displayed in Fig. 4 (b).

C. TASK THREE: LIFTING A BOX FROM THE FLOOR AND PLACING IT ON A SHELF AT HEAD HEIGHT

Increasing the target zones position from a hip level to eye level as seen in Fig. 4 (c) further increases the complexity of coordinating control signals with movements of the arm. Due to the placement of the target at head level or above-head level, the gravity impact on the electrodes and their skin contact is not to be neglected. This can lead to involuntary movements. Thus, this task can be seen as an extension to Task Two.

D. TASK FOUR: PICKING UP A BOX FROM A TABLE AND PLACING IT ON THE FLOOR

Inverting the direction of the task as in Fig. 4 (d) ensures the evaluation of both signal directions. It also implies working together with gravity instead of counteracting it.

E. TASK FIVE: MOVING A BOX FROM RIGHT TO LEFT WHILE AVOIDING A COLLISION WITH AN OBSTACLE

The last task requires the user to control not only the elbow joint, but also the wrist joint. While moving a box from a table on the right hand side to a table on the left hand side, the subject is required to maneuver the grabbed box through an open space in a wall. As the box height is too big to fit the hole, the subject must turn the box, move it through, turn it again and place it on the table. This task is the most difficult to accomplish and depicted in Fig. 4 (e).

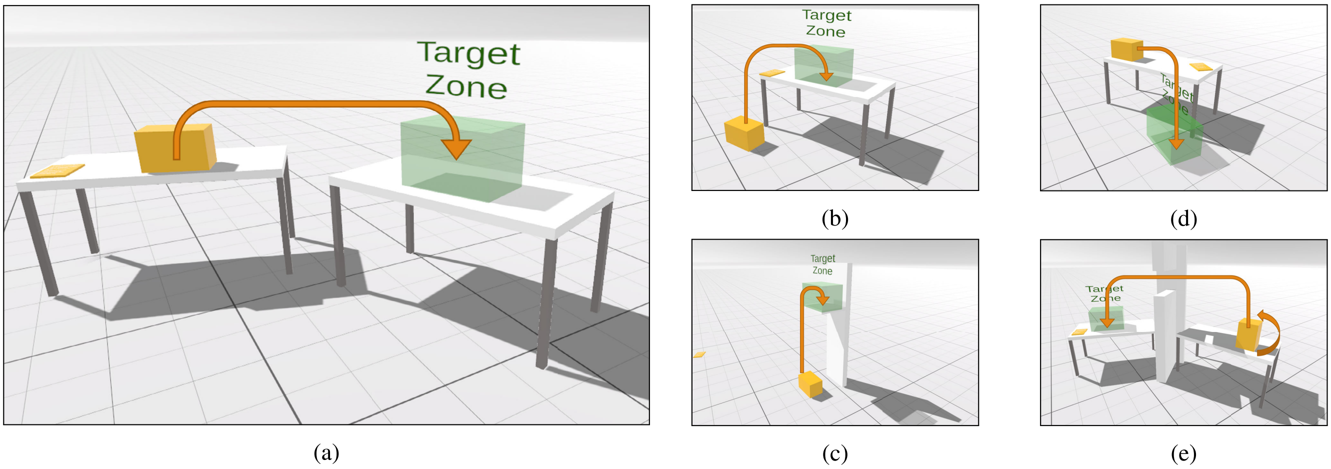


FIGURE 4. Depicting task one (a): moving a box from left to right without height variation, Task Two (b): lifting a box from the floor and placing it above hip height, Task Three (c): placing on a shelf at head height, Task Four (d): lowering a box from a table to the floor as well as Task Five (e): pick up, rotation and collision-free movement of a box from a right to left.

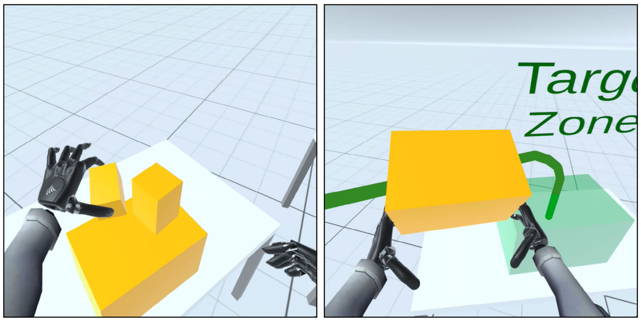
TABLE 1. Properties of each Task.

Property	Task 1	Task 2	Task 3	Task 4	Task 5
Joint Movement	o	+	+	+	++
Joint Switching	-	-	-	-	+
Trajectory Length	o	o	+	+	+
Trajectory Complexity	o	o	+	+	++
Overall Difficulty	o	o	+	+	++

Each task has different demands on the subject, and they are summarized in table 1. Joint Movement describes the difficulty level in positioning a joint and trajectory complexity represents the variation in all three axes.

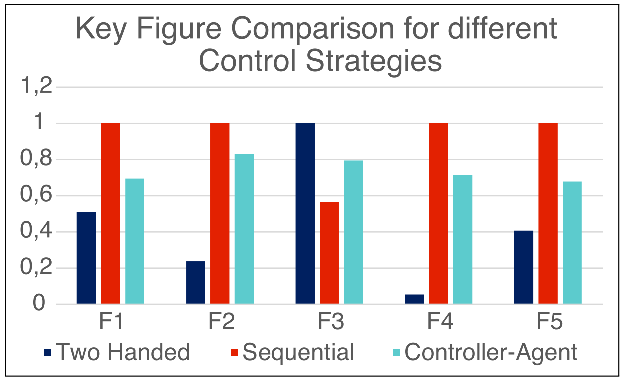
VII. VIRTUAL REALITY EVALUATION SCENARIO

To verify the effectiveness of the quality criterion and the benchmark test, a virtual reality setting is developed in order to have a flexible but physically correct testing environment. By making use of the Unity Physics Engine [12], a precise physics simulation can lead to realistic results. To achieve a highly precise physics interaction, "Articulation Bodies" were used [12]. These allow to make joints follow target movements, while generating torques and forces that affect the interaction with surrounding objects. As virtual reality headset, an Oculus Quest is being used. Based on the built-in four infrared wide-angle cameras, finger- and hand-tracking is being realized. With this, it is possible to control the virtual prosthesis and interact with the environment. The hand tracking maps the users real-world hand position to virtual target position inside the VR environment, where the corresponding virtual hand tries to reach the given target position. A multi-articulated virtual hand prosthesis is realized in this way. If an object collides with the virtual hand, the distance to the target position is used to generate forces and torques which are then again applied to the point of contact between the virtual hand and the collided object. As such, it is possible to grab e.g. boxes in VR based on realistic physical interactions, as displayed in Fig. 5. A virtual arm is realized as well, with one ball-and-socket joint each to simulate the shoulder, elbow and wrist. Through inverse kinematics, the virtual arm arm and shoulder is positioned. Additionally, an arbitrary Bluetooth® interface is created which accepts different type of signals as input to the VR environment. Depending on the selected control strategy, these input signals are translated to motion of the virtual prosthesis. A trigger signal can be sent to switch between the different available joints, and two separate values between 0 and 255 are used to control the joints two directions. The real world hand is again used as target position for the inverse kinematics calculations of the shoulder, elbow and wrist, allowing full motion of the arm and hand. In case of an amputee, the shoulder is left stationary. This also discourages the compensatory shoulder movements which amputees are used to in their daily life. The elbow joint is restricted to one dimension as well, allowing only extension and flexion. The wrist joint is limited to one degree of freedom, rotating around the arm axis to simulate pronation and supination. The end effector, the virtual hand, is position in a flat hand position and cannot be opened or closed currently, which can be improved in future work to also allow fine-grained tasks. The different tasks from Section VI are replicated inside this VR environment and the key figures described in Section V are automatically tracked and recorded while the subject performs the tasks. Inside this testing environment, three different control strategies can be evaluated: two-handed controls for non-amputees, sequential controls and the presented controller-agent control strategy as described in Section IV. The hand-tracking input method is used for the controller-agent strategy, as well as the two-handed manipulations for non-amputees. As to replicate the conventional controls, a VINCENTpartial3 [13] controller is connected to a VINCENTemg2, a compact two channel electromyography sensor [14]. The controller transmits the captured signals wirelessly to the Oculus Quest and

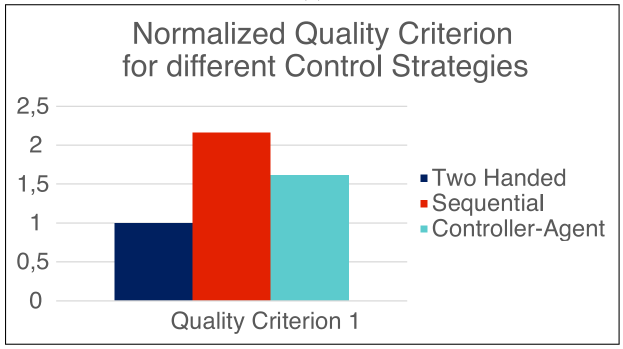


(a) (b)

FIGURE 5. Screenshots from the users perspective inside the virtual reality environment.



(a)



(b)

FIGURE 6. Normalized Key Figures 1 to 5 for each Control Strategy in (a) and the resulting normalized Quality Criterion 2 in (b).

connects to the implemented interface to serve as input to control the different joints as well as for switching between the joints to replicate the sequential control strategy of an elbow and wrist, extending to the hand in a future version. One electrode is connected to each of the two directions and by performing a short muscle contraction, the trigger signal is activated, and the current joint is switched.

VIII. RESULTS

To demonstrate the effectiveness of the presented tools, a small preliminary study is conducted. The execution of the tasks inside the virtual reality environment is performed by five non-disabled subjects, whose informed consents were obtained prior to participating. The three control strategies are used to perform each task described in Section VI, whereas the two-handed manipulation is serving as a benchmark movement. After executing each task, the questionnaire is completed as well, to be able to calculate F_5. The weights for the intra-user criterion were chosen as indicated in Eqn. 6. In order to be able to compare the key figures between the different participants, the mean of each key figure over all participants was normalized with the maximum value of the give key figure's mean for all three control strategies. This leads to the figure displayed in Fig. 6 (a). This normalization allows a comparison between the control strategies per key figure, it should be noted however that a comparison between different key figures is not meaningful. The resulting inter-user quality rating $Q_{\lambda i}Q_{\lambda\text{ref}}^{-1}$ according to Eqn. 7 is shown in Fig. 6 (b). As expected, the two-handed control has better metric for each key figure, except F_3. This might be due to the fact, that the VR simulation picks the first resting position of the target cubes as final position and does not allow for corrective movements. Thus, having more degrees of freedom and being easier to operate, the two-handed movements might not be as accurate in the beginning as other slower controls. This hints at a future improvement possibility of the metrics calculation methods in VR. For each other key figure, two-handed controls outperform sequential controls as well as the controller-agent strategy. The controller-agent strategy is also showing better results than the sequential controls for the remaining 4 figures. In total, the Quality Criterion shows the advantage of the two-handed controls over the other methods and as such can be assumed as a valid evaluation value to determine the performance of different control strategies. Even though the presented results are based only on five users, they show the capability of the presented Quality Criterion in regards to performance evaluation of different control strategies.

IX. CONCLUSION

In contrast to previous work on upper arm prostheses controls, we focus on bilateral tasks as facilitating these, opposed to single handed activities, bring the amputee the most benefit. A new taxonomy for bilateral tasks is presented as well as a quality criterion based on five different newly defined key figures, enabling us to compare our proposed control strategy to existing or even upcoming new ones. The taxonomy allows for a detailed and clear categorization of bilateral actions and can serve as a basis for different classification projects. Five different tasks are developed to have a benchmark test for evaluation of control strategies. These tasks are realized in a virtual reality environment and based on this it is shown that the presented criteria are able to discern different control strategies and allow for evaluation of such methods, thus paving the way for an evaluation study with non-disabled and amputees in order to determine whether patients would benefit from the newly presented Controller-Agent control strategy and to clearly identify the true needs and benefits of different controlling methods. The outcome of the present work can also be transferred to other research areas. As for the taxonomy, it can e.g., serve as a categorization for activities of daily living analysis. The benchmark test can also be realized in different settings such as rehabilitation, progress monitoring or even extended to evaluation of control systems for humanoid robots. It can be used to rate the reliability of robotic systems as well as serving as a benchmark for AI-controlled robots which need to complete bilateral tasks designed for humans. Thus, the here presented findings do not only serve in optimizing prosthetic systems but can also be repurposed on a variety of other applications.

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