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Do we need complex rehabilitation robots for training complex tasks?

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***Abstract*— One key question in motor learning is how the complex tasks in daily life – those that require coordinated movements of multiple joints – should be trained. Often, complex tasks are directly taught as a whole, even though training of simple movement components before training the entire movement has been shown to be more effective for particularly complex tasks ("part-whole transfer paradigm"). The important implication of the part-whole transfer paradigm, e.g. on the field of rehabilitation robotics, is that training of most complex tasks could be simplified and, subsequently, devices used to train can become simpler and more affordable. In this way, robot-assisted rehabilitation could become more accessible. However, often the last step in the training process is forgotten: the recomposition of several simple movement components to a complete complex movement. Therefore, at least for the last training step, a complex rehabilitation device may be required.**

In a pilot study, we wanted to investigate if a complex robotic device (e.g. an exoskeleton robot with many degrees of freedom), such as the ARMin rehabilitation robot, is really beneficial for training the coordination between several simpler movement components or if training using visual feedback would lead to equal benefits. In a study, involving 16 healthy participants, who were instructed in a complex rugby motion, we could show first trends on the following two aspects: i) the part-whole transfer paradigm seems to hold true and therefore, simple robots might be used for training movement primitives. ii) Visual feedback does not seem to have the same potential, at least in healthy humans, to replace visuo-haptic guidance for movement recomposition of complex tasks. Therefore, complex rehabilitation robots seem to be beneficial for training complex real-life tasks.

I. INTRODUCTION

Many experts in the field of neurorehabilitation agree that motor recovery is a form of motor learning [1]. Therefore, motor learning and motor rehabilitation go hand in hand [2][3]. Since most tasks in daily life involve complex motions (namely, motions which involve more than two degrees of freedom, require more than one session to learn, and are ecologically valid [4]), motor rehabilitation has a big interest in improving the patient's function for such complex real-life tasks. In this context, motor rehabilitation can profit from the research results in motor learning of complex tasks (e.g. 3D trajectories [5], tennis [6], rowing [7], bouncing balls [8], ...). The research efforts in motor learning resulted in several valuable guidelines to design training [9] and feedback [10] systems. Closely related to research on complex movements are the investigations on inter-joint coordination mechanisms for well-coordinated motion. There are two main paradigms in the domain of complex motion learning: the "part-whole transfer paradigm" and the "task-oriented training paradigm".

The part-whole transfer paradigm states that integration of single components of a motion can be enhanced when these components are trained separately and, afterwards, integrated together (e.g. in [11]). Several studies showed that independent practice of several joints was successful to learn a tennis stroke [12], or at least perform as well as practicing the full motion (e.g. for a sequential tapping task [13]). Also successful part-whole transfer results were shown in a video-gaming setup [11].

The second paradigm in motor learning literature is the "task-oriented training paradigm", which states that the correct realization of a motion requires practice of the full motion. For example in [4], several arguments are provided suggesting that training paradigms, which are valid for simple skills, may not be applied for training complex skills. In [14], the authors state that the single motor primitives can only be replayed in a coordinated way when the full complex motion is performed.

In this work, we want to investigate if the part-whole transfer paradigm holds true in a complex rugby task, i.e. part-whole transfer is superior to learning the complex task at once (Group 1). For creating simple movement primitives, we choose decomposition of the movement into anatomical components (Group 2), which was the most effective movement decomposition in a previous study for a tennis task [12]. Additionally, we are interested in understanding how important the haptic component is for learning a complex movement in comparison to the visual component. Therefore, we include a group that obtains only visual feedback for the recomposition of the visuo-haptically trained simple movement parts (Group 3). In a fourth group, we only provide visual feedback in training and recomposition repetition (Group 4).

The design of this study was inspired by a previous study of Klein et al. [12]. We hypothesize that breaking down a motion anatomically might not be enough, as proposed in [12]. To our knowledge, the importance of practicing the full motion, as an essential part of the part-whole transfer

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paradigm, remains unexplored; reason why we tried to study the role that the whole motion recomposition (i.e. whole training) plays on the part-whole transfer paradigm. For this and for comparability reasons of our study with Klein et al., we employed the same study design (protocol and groups 1 and 2) and also performance metrics. The goal of the replicating part of our study was to confirm the part-whole transfer, but on a different movement: the 5 degrees of freedom rugby movement.

The goal of the herein described pilot study was to understand if we need complex rehabilitation robots for training complex movements. The starting point, therefore, was to test if first breaking down a movement into its primitives by anatomical angles and after recomposing those primitives promotes higher performance gains than permanent training of the entire movement (hypothesis 1). A confirmation of the part-whole transfer paradigm would indicate that different movement components could be trained on several simple robotic devices instead of one complex device. Further, we investigated a second hypothesis to clarify if visuo-haptic feedback would be superior to visual feedback only for recomposing the simple movement parts to a complex movement (group 3). We expected a better retention in visuo-haptic feedback groups due to a more stable and permanent *motor memory* mediated by provision of haptic feedback as in [6]. Finally, to understand the importance of haptic feedback used in combination with the part-whole transfer paradigm (both for training the components of a motion or the full motion) we measured motor learning of a group provided with visual feedback only (group 4). In case this group would perform better than groups 1, 2 and 3, then virtual reality (VR) based systems (i.e., no haptic feedback) would be sufficient for training complex tasks, at least in healthy humans. We hypothesized, though, that visuo-haptic training would be superior to visual only training, for learning the motion selected for this study (hypothesis 3).

II. METHODS

A. Research question and hypotheses

This pilot study aims at investigating to which extent visuo-haptic recomposition of a complex motion, following the part-whole transfer paradigm, is necessary for training complex real-life tasks. To do so, we tested the following three hypothesis:

- **H1:** Part-whole transfer based training of movement, using anatomical components, enhances motor learning of a complex rugby motion; as compared to training the entire movement only.
- **H2:** When learning a full complex motion, visuo-haptic recomposition of the previously separated components is superior to visual recomposition.
- **H3:** Visuo-haptic training is better than visual only training.

B. Group design

The three hypotheses were tested based on group-wise comparisons of the following four groups (Fig. 1):

- **Group 1:** *Whole coordination training*: The participants assigned to this group received visuo-haptic feedback of the target motion during the 8 *training* repetitions and the following *recomposition* repetition (see Fig. 4) with the help of the ARMin 4+ robot.
- **Group 2:** *Anatomical coordination training*: During the 8 *training* repetitions, the participants of this group experienced a randomized visuo-haptic feedback of the motion, either on the part of the motion corresponding to arm swing[1] or the forearm spin[2](i.e. anatomically decomposed training). Later, in the *recomposition* repetition the complete motion was demonstrated visuo-haptically (see Fig. 4) with the help of the ARMin 4+ robot.
- **Group 3:** *Anatomical haptic training*: The participants of this group received visuo-haptic anatomical feedback, with the help of the ARMin 4+ robot, during the 8 *training* repetitions similar to group 2. However, during the *recomposition* repetition, only visual feedback was provided (see Fig. 4).
- **Group 4:** *Anatomical visual training*: This group received only visual feedback on the anatomical components of the motion during *training*. During the *recomposition* repetition, visual feedback on the entire movement was provided. Even if no haptic feedback was provided, the participants were always training inside the ARMin 4+ robot, however in transparent mode [15]. This procedure should ensure similar experience of the task dynamics as compared to the other groups.

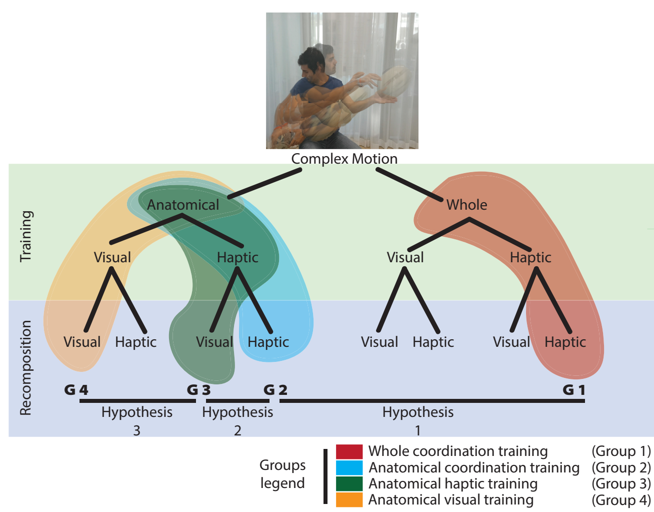


Fig. 1: The group design chart illustrates the chosen feedback designs for the training and recomposition repetitions for the four groups.

C. Task Description

A rugby drilled pass, in two variants (lateral and frontal) was selected as a motion. The lateral pass was used as

[1]Arm swing motion comprised shoulder motions only (i.e. shoulder abduction/adduction, shoulder elevation or flexion/extension and shoulder internal/external rotation).

[2]Spin motion comprised forearm motions only (i.e. elbow flexion/extension and pronation/supination of the forearm).

a target motion and the frontal pass as a transfer motion, to study generalization of the learned skills [2]. The rugby drilled pass, which includes motions in 5 axes with a large range of motion (RoM), is an ecologically-valid task (i.e., not an artificial laboratory task), and therefore, meets the definition of a complex movement according to [4]. Additionally, it includes several bio-mechanical aspects that increase the level of complexity compared to simple tasks, such as spin, coordination, and optimal projection [16] (see upper part of Fig. 1).

The coordination pattern and kinematic features of the target motion differed substantially from those of the transfer motion in terms of maximum speed attained and RoM (of each of the joints involved in the motion). As mentioned above, the transfer motion was investigated to study generalization of the learned skills. However, results relating transfer motion are not included in this paper.

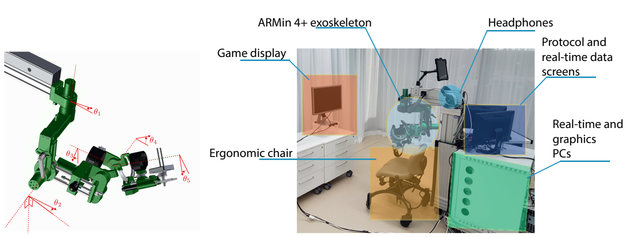
D. Participants

The study was conducted at the Balgrist Campus within the Sensory-Motor Systems Lab of ETH Zürich.

A total of 16 participants (11 males, aged 20-31 years) were recruited among the employees of Balgrist campus and students of ETH Zürich and randomly assigned to one of the four groups. The inclusion criteria for the study were: right-handedness, naivety to the task (i.e. rugby pass), healthy or corrected to healthy vision, no medical history of motor disorders or shoulder/elbow related pathologies. The participants conducted the study under the VIT-ARMin ethical approval issued by SwissMedic (clinical trial 2015-MD-0004 VIT-ARMin). All participants provided signed consent for their participation.

E. Experimental setup

For this study, the ARMin 4+ exoskeleton rehabilitation robot was used [15]. ARMin provided either haptic guidance or stayed in transparent mode in order to allow the participants to move freely.



(a) ARMin 4+ (b) Experiment's configuration.

Fig. 2: ARMin 4+ system used for the experiment.

ARMin 4+, is a 7 degrees of freedom exoskeleton robot (Fig. 2), which is used for arm rehabilitation. During the experiment, only the following five axes were used: shoulder abduction/adduction, shoulder extension/flexion, shoulder internal/external rotation, elbow flexion/extension and forearm supination/pro-supination. The arm of the participant was aligned with the robot through the lower and upper arm cuffs, which were fixed to the respective robot links.

ARMin 4+ has 3 six-axis force/torque sensors (FTS) located at the hand, lower arm, and upper arm. The FTS are used for acceleration control of the robot with the help of Disturbance Observers (DOBs) [15]. Explicit acceleration control is achieved by matching the task space wrench $\boldsymbol{\tau_t} \in \mathbb{R}^6$ and sensor measured wrenches $\boldsymbol{\tau_s} \in \mathbb{R}^{18}$ as projected onto the ARMin's strucure via ARmin's Jacobian (here as $\boldsymbol{\tau_{int}} \in \mathbb{R}^5$). If position control is desired (i.e. make the joint angles, $\boldsymbol{\theta} \in \mathbb{R}^5$, follow the reference movement, $\boldsymbol{\theta_r} \in \mathbb{R}^5$), any desired second-order dynamics ($\ddot{\boldsymbol{e}} + \boldsymbol{K_d}\dot{\boldsymbol{e}} + \boldsymbol{K_p}\boldsymbol{e}$; $\boldsymbol{e} = \boldsymbol{\theta_r} - \boldsymbol{\theta}$) can be enforced by ($\boldsymbol{\tau_t} = \boldsymbol{J_N}[\,\ddot{\boldsymbol{\theta}}_{\mathbf{r}} + \boldsymbol{K_d}(\dot{\boldsymbol{\theta}}_{\mathbf{r}} - \dot{\boldsymbol{\theta}}) + \boldsymbol{K_p}(\boldsymbol{\theta_r} - \boldsymbol{\theta})\,] + \boldsymbol{\tau_{int}}$), where $\boldsymbol{\tau_{int}}$ are the measured interaction torques and $\boldsymbol{\tau_t}$ are the desired torques for a given motion, dictated by the control gains (i.e. $\boldsymbol{K_d} = [100]_{5x1}$ and $\boldsymbol{K_p} = [20]_{5x1}$) with units $[\boldsymbol{K_d}] = s^{-1}$ and $[\boldsymbol{K_p}] = s^{-2}$. The nominal inertia matrix ($\boldsymbol{J_N}$) was defined for each joint of the robot ($[\boldsymbol{J_N}] = Kg \cdot m^2$). This also applies if velocity control is desired. In this study, a trajectory control (enforcing PD law, i.e. position and speed) is used.

In addition to haptic feedback, ARMin provided also visual feedback (see Fig. 3). Visual feedback provided the knowledge of performance in the form of a visualization of two virtual avatars: one semi-transparent avatar as the reference and a solid avatar representing the participant. Knowledge of results was provided in the end of the repetition in terms of trajectory shape error (see upper part of Fig. 3).

ARMin was controlled by an external target PC (xPC). The communication between the graphics PC and the xPC was realized by TCP/IP and UDP protocols. A graphical user interface in Unity3D allowed the experimenter to operate ARMin and to select the visual feedback that was shown to the participant on an additional game display in front of the participant. Additionally, in order to control the auditory stimuli of the participants, a homogeneous and constant background sound (*white-noise like* crowd clamor of baseball match) was played on a pair of headphones (see Figures 2). Finally, the participants' motion data of the 5 degrees of freedom used in the study was obtained from encoders in ARMin's joints at 1.8kHz.

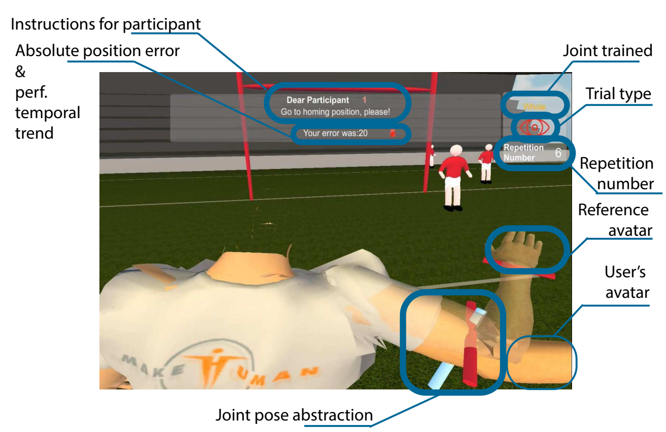


Fig. 3: Visual interface for rugby training.

F. Experimental protocol

All participants underwent the experimental protocol (similar to the protocol used in [12]) in two sessions. Session 1 consisted of Baseline tests of target motion followed by the transfer motion, training of the target motion and a final test of target and transfer motion. Session 2 was performed one week later and consisted of retention tests of target and transfer motion (see Fig. 4). Before (each) Baseline, i.e. target and transfer motion practice, all participants obtained two video explanations of the task they would be asked to perform. During baseline and retention, participants received only visual feedback while being strapped into the ARMin robot that was set to transparent mode. Short-term retention (Retention 1) and Long-Term Retention (Retention 2), as depicted in Fig. 4, to replicate Klein et. al.'s study [12] and following recommendations from existing literature relating the correct design of motor learning experiments [2].

The Baseline consisted of 12 repetitions (6 repetitions of the target motion and 6 repetitions of the transfer motion). The training phase (100 repetitions long) involved 10 series of practice blocks. Each practice block contained ten repetitions of which 8 were *training* repetitions (in green), 1 was the *recomposition training repetition* (in blue) and the last one was the *test repetition* (in red). Participants trained only the target motion during training according to their group assignment. Short & Long-term Retention blocks (Retention 1 and 2) had a similar structure as the Baseline. In the test repetitions (in red in Fig. 4) participants were evaluated and received no feedback (nor haptic or visual, just the own participant's arm was projected in the form of a solid avatar arm). Only the score (i.e. mean absolute tracking error in the joint space, see eq. 1) was provided in the end of the test repetition with an indication of whether they improved or worsened with respect to the previous repetition (see upper part of Fig. 3).

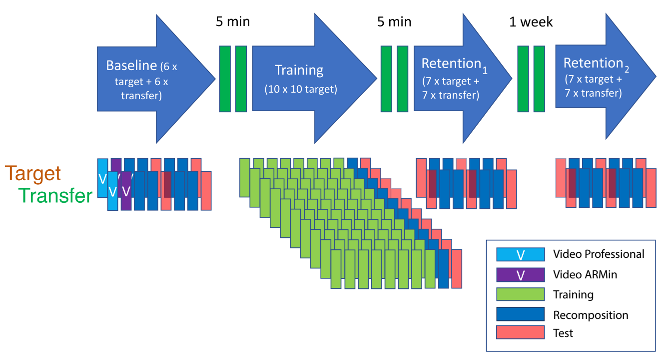


Fig. 4: Experimental protocol.

The protocol was automated, to avoid human mistakes and preserve the same experimental conditions across participants. The presentation of each component of the motion was pre-randomized with a changing seed (done in MATLAB®) and stored on a file which was loaded for each participant. The number of components practiced (arm swing or spin) over the full protocol was the same for all participants.

G. Data analysis

In post processing, the data was cut into single movements for each test repetition and participant. The criteria defining the start and the end of each individual motion was set to 10% of the maximum speed of the shoulder abduction/adduction and elbow flexion, for both the reference and participant's trajectory. After definition of motion start and end, the data of all five joints were resampled to time intervals corresponding to increments equivalent to 0.5% the full cycle of the participant's and reference motion. The resampling algorithm used a 5^{th} order spline to reconstruct the path of each degree of freedom of the motion (i.e. participant's and reference joint motions). Resampling was performed for both the participant as well as for the reference data to allow a direct comparison of kinematic parameters at a given percentage of movement completion, avoiding possible delays in motion onset and compensating wrong replication of motion duration.

To assess motor learning, position error was selected as an outcome measure. The reasons were several: participants were trained in the joint domain, position error is a common metric in the field of motor learning (e.g. [8], [12], see review [17]), and we wished to partially replicate Klein's study [12] and to compare our results. The norm of the mean absolute position error was computed as follows:

$$\epsilon_\theta = \left\| \frac{1}{C} \sum_{0}^{C} |(\theta_{\mathrm{R}}(c_i) - \theta_{\mathrm{S}}(c_i))| \right\|, \tag{1}$$

where ϵ_θ is the mean absolute tracking error in the joint space, $\theta_{\mathrm{R}}(c_i)$ is the resampled reference angle at cycle instant c_i, $\theta_{\mathrm{S}}(c_i)$ is the resampled participant's angle at cycle instant c_i and C is the full percentage of the trajectory cycle (i.e. C = 100 %). This metric gives information about the trajectory shape correctness.

Statistical analysis was performed to test the hypotheses. All hypotheses testing was done in terms of *improvements*, e.g. decrease of error between baseline and the end of the training, retention 1, and retention 2; taking the average error of each phase (i.e. total of three test repetitions). The last 3 repetitions of the training were averaged. These obtained improvements were normalized with respect to baseline performance in order to diminish expected effects of different levels of initial skills.

Normality and homogeneity of the variance tests (Shapiro-Wilk and Levene's homogeneity test, respectively) were performed. Given that the assumptions were violated, non-parametric testing was conducted. For this, Kruskal-Wallis one-way ANOVA was used in order to find significant differences between groups. Post-hoc tests (one-tailed Mann-Whitney U-test) was used for mean comparisons of the different groups. The comparisons performed aimed at testing our three hypotheses: Hypothesis 1: Superiority of part-whole transfer, using anatomical training, over training the entire movement (i.e. group 1 *vs* group 2); Hypothesis 2: Superiority of haptic recomposition over visual recomposition (i.e. group 2 *vs* group 3); Hypothesis 3: Superiority of haptic training over visual training (i.e. group 3 *vs* group 4)[3].

III. RESULTS

The learning progress of the four groups was quantified over the four trial phases in terms of the normed mean error over the five joints for each participant. Data is visualized in form of learning curves for each group indicating mean and standard deviation (see Fig. 5).

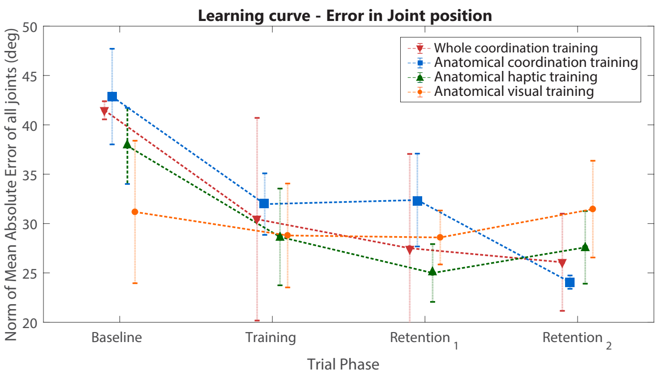


Fig. 5: Evolution of the participant's error in position across test repetitions. Bar graphs are used to provide the standard deviation.

Kruskal-Wallis test was conducted for all comparisons between different trial phases with respect to Baseline (Fig. 6). The first test compared Baseline to the end of the Training and revealed non-significant difference between groups: H(3)=1.390, p>0.1. Also, from Baseline to Short-term Retention, no significant difference between groups was found: H(3)=1.831, p>0.1. However in Long-term Retention, a tendency between groups was found: H(3)=5.890, p=0.1. As an exploratory analysis, to further understand this trend, each hypothesis was tested separately with pairwise testing (Mann-Whitney U Test). Pair-wise comparisons between groups revealed a significant difference between the median of Group 2 (Mdn=18.25%) and the median of Group 3 (Mdn= 24.21%): U=2.00 , z = 1.732, r=0.61 large effect, p<0.05 (Fig. 6). Trends can be identified though, pointing out that Group 2 (being trained with anatomical haptic decomposition and haptic recomposition) could outperform the other groups (see Fig. 6).

IV. DISCUSSION

This pilot study was motivated by the question whether it is possible to replace complex robotic devices by simpler robots for training complex real-life tasks. To tackle this question, we have set up three hypotheses to answer this question in steps.

The first hypothesis stated that learning a complex movement by first learning its simpler components before training the entire movement (part-whole transfer paradigm) is more

[3]Significance level was set for $\alpha = 0.05$ for all tests. The statistical software SPSS Statistics[18] and R[19]. Cohen's guidelines for effect size acknowledge a large effect being .5, a medium effect being .3, and a small effect being .1 [20].

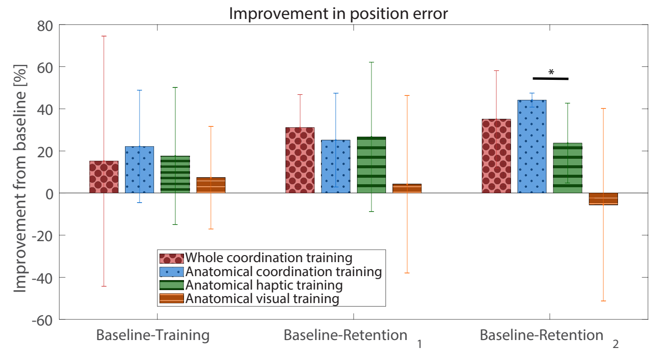


Fig. 6: Relative improvement (w.r.t baseline) of each group. Significant group difference p<0.05 marked with *.

effective than permanently training the entire movement. This hypothesis has already been demonstrated to be valid in several other tasks, e.g. [12][11]. However, we wanted to show validity of this paradigm once more on a complex rugby movement. In our case, due to our low sample size (subsequently, low power) we did not find statistical significance when comparing the learning progress between groups at any of the experimental phases. Therefore, we could not confirm the shared hypothesis with Klein et. al. [12] in our setup. However, it is clear (Fig. 6) that the reduction of trajectory shape errors was of higher extent for Group 2, which was already the most successful in [12] speaking in favor of anatomical coordination training versus any other modality. Besides sample size, another possible reason for differences in results could be the different tasks. In this study, the task might have been more complex than the task used in Klein's study. In such case, instruction of the full motion, haptically, more than once per training round could turn out to be crucial. Conversely, if this first hypothesis would have been true, one could use several simple robotic devices for training simple movement components and only one complex device would be needed for training the complex overall movement (the so called ”Gym of robots” concept [21]).

The second hypothesis tested whether using a complex robotic device brings additional benefits for recomposing the simple components of a complex movement or if visual feedback alone is equally beneficial for recomposing those components into a complex motion. With our specific experimental setup, we statistically explored this hypothesis and we could accept this one, as there was a significant large positive effect of visuo-haptically instructing the full motion, as compared to visually recomposing this full motion, just after anatomical training of the separate movement components. We are aware that even if this hypothesis might be true in healthy participants, it would need to be proven with patients (e.g. including different stroke aetiology) as they might lack of the necessary force to be able to recompose the movement components to achieve the complex target movement. As this hypothesis turned out to be true, complex rehabilitation devices would be beneficial, as recomposition of complex movements based on visual feedback (e.g. a VR gamified setup) would be insufficient.

In this study, we could not find statistical grounds to confirm hypothesis three (i.e., visuo-haptic training would be superior to visual only training); due to, mainly, our low power (as a consequence of a low sample size). However, we could observe trends in line with the hypothesis, specially in long-term retention. Additionally, the fact that hypothesis two was accepted supports partially hypothesis three, as haptic feedback is indeed helping in learning a complex motion. If the third hypothesis would have been rejected, even simple robotic devices would be obsolete as visual feedback (e.g. virtual platform for rehabilitation) would be enough for learning simple and also complex tasks.

We are aware that our pilot study did not include enough participants per group to provide the required statistical power. However, we were interested in seeing if the effect sizes were big enough for the chosen task, the chosen groups, and chosen metric in order to perform a comprehensive study on the same or similar research questions (maybe including patients). Even if we cannot show statistical differences in many aspects, we could already find a tendency for significant group differences in the learning from Baseline to Retention 2 (one week after training). At closer look, post-hoc tests revealed a significant group difference between Group 2 and Group 3, confirming hypothesis two (i.e., visuo-haptic feedback on the complete task outperforms visual feedback only). Therefore, our main question when posing this study is answered: visuo-haptic recomposition of a complex motion is beneficial for training complex real-life tasks. As a consequence, complex rehabilitation devices, like ARMin rehabilitation robot, may still bring additional benefits to the training of complex tasks, both for supportive purposes and to enhance neural mechanisms promoting motor learning.

V. CONCLUSION

In a pilot study, we investigated to which extent complex robotic devices (e.g. exoskeletons) would be needed for training complex real-life movements. To tackle that question, we tested the following point: Would visuo-haptic recomposition of a previously anatomically broken down full-motion be more beneficial for motor learning than visual only recomposition? To answer this question we studied motor learning of a complex real-life rugby motion.

Despite the small sample size, we found indications that visuo-haptic recomposition of the full motion seems to yield to stronger learning effects than visual feedback alone, which speaks for the importance of practising the full-motion haptically. Additionally, this fact highlights the role of complex robotic devices, which are capable of demonstrating the full motion coordination aspects while also enabling to train aspects relating the simpler movement components. Finally, this experiments serves as a validation of the study design and, thus, more experiments will follow which will aim to bolster the results presented in this article.

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