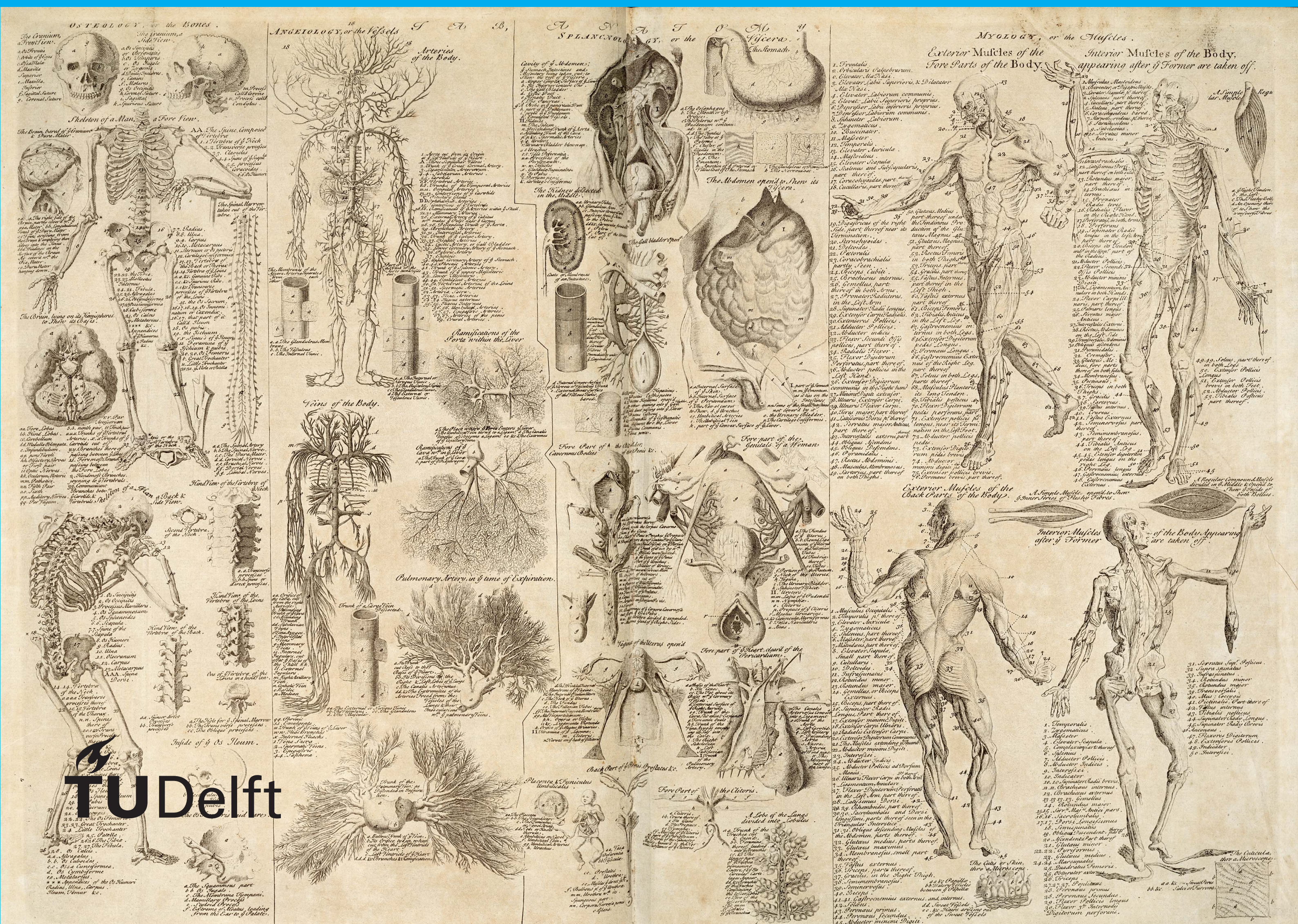
Master Thesis

On motor learning

J. Peñalver-Andrés

Title:

*Is breaking it down better?:
Enhancing motor learning via controlled sensory-motor integration*



TU Delft

Master Thesis

On motor learning

Is breaking it down better?: Enhancing motor learning via controlled sensory-motor integration

by

J. Peñalver-Andrés

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TU Delft

Abstract

Complex motions are generally accepted as movements which consists of at least 2 Degrees of Freedom (DoFs) actuated in a coordinated manner, which takes more than one practice session to be mastered, and that are ecologically valid (see [87] for a clear statement).

The techniques to teach and re-teach (also, (re-)learn) a complex motion are thoroughly investigated by the motor learning research community since decades and up to know. There is certain agreement on the theses of practice intensity and duration as a factor for learning. However, the content of the practice sessions is still, only, partially understood. One point which is still to be confirmed is the "Part-whole transfer" paradigm[36]. This theory promulgates the fact that motions are rather a composition where alphabet items are skillfully combined to produce a dexterous movement and that the better the "alphabet" is known, the faster the learning will be and dexterous the result. The importance of the whole practice of a full motion remains still unknown.

Our hypotheses were that inclusion of the full motion is crucial for correctly learning a complex motion pattern. We hypothesized, also, that the way of re-composition of a motion would play a role in the performance after the training and the retention of the learned skill, as well as the transferability of its fundamentals to a new skill.

In this thesis, these questions are investigated. For this, an experiment with 16 healthy subjects has been conducted. The subjects where pseudo-randomly assigned to one of the following groups: whole visuo-haptic coordination training, anatomical visuo-haptic coordination training, anatomical visuo-haptic training and anatomical visual-only training. The importance of the haptic coordination training (i.e. practice of the whole motion together) was investigated in the first two groups, while the coordination pattern was shown only visually in the last two groups. Additionally, the way of showing the single components (anatomically or holistically) and the type of feedback (visual-only or visuo-haptic) was investigated in the different groups designed.

The results showed that the full trajectory is better learned by subjects who were shown the full motion visuo-haptically (opposed to only visually). The transfer and the consolidation of the motion pattern (also translated into a better retention) are also benefited by adding special emphasis to the single components of a motion first (Group 2). Only the training of the speed profile is benefited by more practicing the full motion visuo-haptically (i.e. group 1). All these aspects have, obviously, an impact in motivation. The groups which were more guided (i.e. visuo-haptic full motion guidance) felt less pressure, committed with less effort but got higher sense of competence and more motivation, not necessarily translating in better performance (somewhat in agreement with the Guidance Hypothesis).

The results of this study contribute to the field of motor learning bringing some more insight in the mechanisms of complex motion learning and could have a transfer to the clinical practice to improve re-learning of lost motor skills (e.g. after a stroke).

Keywords: *Motor Learning , Part-whole Transfer , Robotic Training , Complex Motion , Exoskeletons.*

Preface

What you are about to start reading, i.e. *"Is breaking it down better?: Enhancing motor learning via controlled sensory-motor integration"* is the written result of a research project with topic: motor learning. The goal of this document is presenting the knowledge gathered during my research experience to provide researchers, rehabilitation personnel and sport coaches with valuable scientific groundings to structure the training of complex motions. It has been written as part of the graduation requirements for the program Master of Science in Biomedical Engineering, at TU Delft, Netherlands. I was engaged in this research since late June 2017, until the finalization of this report in January 2018.

The results and methods presented in this work are just the summit of a long process (of about 1 year) in which I have discovered the groundings of this scientific field (i.e. motor learning) from the motor learning theories, understanding of human controller, understanding of complexity sources of a motion to finally getting to know the strategies and techniques to teach a complex motion. The crystallization of this preliminary research is presented on this work as an experiment whose aim is understanding the importance of learning simpler sub-components of a complex motion before facing up the full complexity of this one. Several ways of integrating the sub-components are analyzed in this work. These works have been undertaken as exchange student at ETH Zürich, concretely at the Sensory Motor Systems Lab (lead by Prof. Robert Riener). The work was jointly supervised by Prof. Heike Vallery and Prof. Georg Rauter, with the kind co-supervision of Prof. Laura Marchal-Crespo and Dr. Jaime Duarte.

The scientific relevance of this work is not only limited to the field of motor learning for teaching complex motions in sports. Instead, the results and conclusions of this work might have in the future a big impact in neuro-rehabilitation in what relates to regaining complex motor patterns which are essential in the daily living of patients suffering of motor disorders. However, the limitations of this work, mentioned in the Conclusion section, allowed only for a feasibility pilot study during my master thesis period. Despite of this, it is my supervisors' plan, and mine, continuing this research work to find its implication in the neuro-rehabilitation field.

Academically, this work has allowed me to materialize the education I have received in both the pure technical topics, during my studies in Engineering in both Spain and Germany, the more medical-related topics, gained during my studies at TU Delft, and all the organizational and product related topics, mainly resulting from several endeavors I committed to, during my education, such as Project MARCH. I would definitely recommend other students to take such a challenge where I learned all kinds of skills: from game development to neuro-science.

For giving me this education opportunity, I would like to thank all my supervisors: Prof. Heike Vallery, Prof. Georg Rauter, Dr. Jaime Duarte, Prof. Laura Marchal-Crespo, Dr. Verena Klamroth-Marganska. Also I am vert thankful to Prof. Robert Riener and Dr. Peter Wolf, for hosting me at the department they lead. From them I have learned how to properly design, plan, implement and analyze experimental outcomes of a motor learning study. I have benefited specially from their expertise on the field which also reflected on the corrections of this document. For all your academic imprint, thanks.

Finally, I need to specially thank my colleagues at the Balgrist Campus, also known as "*Minions*". To all of them, I would like to thank the very interesting talks in the coffee breaks and the amazing working atmosphere which allowed us achieving so much. I would like to thank specially, Adrian Vogel, Stefano Tortora and my current work colleague Özhan Özen for helping me taking some decisions. For their constant support I would like to thank the Delft's delegation at ETH (Severine, Felix and Miguel), which supported each other's dreams since we started at TU Delft. For her immense support and love, I would like to thank Samantha Weber who really helped when the motivation dropped down. My family is always in my acknowledgments, not only for obvious reasons, but for being the main responsible party of my curiosity for the medical application of my engineering education. Their wise counsel and kind motivating words have always kept me on my way.

In general, to all those who contributed to my character and education: Thank you.

I hope you enjoy reading this work.

J. Peñalver-Andrés
Delft, January 2018

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1
Introduction

Motor learning was born as a branch of experimental psychology where researchers develop their interest in the mechanisms mediating learning of motions both from the physiology and the psychology postulates. Later, when the field merged with human factors engineering research, the research has translated to more applied research, where training strategies have been investigated which mediate learning based on the postulates of experimental psychology[61].

Several fields nourish and flourish from the knowledge acquired in motor learning, from medical applications (e.g. surgery or motor rehabilitation) to sports applications, passing by military applications where the field of human information theory, one of the roots of motor learning, started[25]).

One of the open questions in the field is how to train is training of complex skills or movements. First, a definition of skills is needed. Guthrie [31] defined skill as “the ability to bring about some end result with maximum certainty and minimum outlay of energy, or of time and energy” (see [72] for more information). In this work we focus on motor skills, therefore we see skills as *motions* which meet the previous criteria in terms of performance and acquisition. Several authors have been occupied understanding the differences between learning a simple and a complex task ([86]). The commanding rules which serve as a model for the human to generate complex motions have also been studied in [60][28].

In this work, our focus is understanding how *complex motions* are mastered. Therefore, a definition of complex skills/movements is needed. Complex motions are generally accepted as movements which consists of at least 2 Degrees of Freedom (DoFs) actuated in a coordinated manner, which takes more than one practice session to be mastered, and that are ecologically valid (see [87] for a clear statement). Conversely, a simple task is learned within one session of training and contains simple DoF motions and look more artificial. Other authors have defined the features that influence complexity of acquiring a complex skill[27] (e.g. amount of information available about the task's goal, speed of the motion, etc.). Also, some other authors have defined skills or tasks upon some parameters: discrete/continuous, fine or gross, open/closed (depending on the external influences), self-/externally paced[71]. Finally, a task can become more complicated by adding goals or cost functions that are to be maximized [43] (e.g. throwing a ball with maximum attained distance). Anyway, in[85] the use of more complex motions is suggested, to mediate a more comprehensive understanding of the mechanisms of motor learning and control, as opposed to the traditionally used artificial (namely, "lab") tasks. Some efforts in terms of studying complex motions have already been done by several research groups around the Globe. Examples of these interventions can be (e.g. 3D trajectories[22], tennis[52], rowing[74][65], handball[78], bouncing balls[53], tai-chi practice [77], archery[29], rugby pass[55],...). The field is prolific, and several valuable guidelines have been drawn for the design[65][35] and use of technology-based systems[73]. Given the guidelines and research available, one of the goals of this study is designing a complex task in order to gain meaningful information about the motor learning processes involved in the learning of complex coordinated motions. The respective information will be provided in the corresponding section.

An important topic on the design of such systems are the feedback modalities used for mediating motor learning. It is known that visual feedback is beneficial for shape learning of trajectories[22], especially when it is given in a concurrent way instead terminal feedback (also known as *knowledge of results*)[12]. Also, it is known that seldom terminal feedback (i.e. knowledge of the results) helps improving in the next runs of practice, in combination with concurrent knowledge of performance (i.e. online information about the motion correctness) [8]. Haptics has been found to help learning the shape of trajectories [22] complementing the visual stream information. Note that learning can have an immediate effect (skill to reproduce a taught motion) and can also have a long-term effect (i.e. over several days, weeks or months, also known as retention). Haptics has been found especially useful for learning of speed profiles of motions [74][52] of time-critical tasks (e.g. tennis serve), while for discrete tasks (e.g. learning the acceleration at impact of a tennis hit) it was found detrimental[53]. Auditory cues seem to also persist in time (i.e. good retention)[74], as well as vibratory feedback which is modulated by a good matching metaphor (i.e. resembles the message it wants to transmit) [65]. All these gains can be complemented, if done properly, in order to provide augmented multi-modal feedback. When done properly, it can trigger "inter-sensory facilitation". These are mechanisms which improve the performance of the motor learning protocol by distributing the information among different channels, bolstering acquisition of the skills and retention, by co-activating different brain areas which are related to association processes [73].

There are other factors which influence, mediate and modulate motor learning. There seem to be a need to adapt or adequate the training to the task type [53], the level of skills of the practitioner [19][52][74], the cognitive load which they are subject to(e.g. the among of information that has to be processed [80], where the focus is put[88] or the emotional status of the subject[19]). This project will not focus on these effects as learning mediators but more as a result. Therefore, analyzing the effect of training in these variables is a part of this project.

Another challenge faced by the research community is understanding the inter-joint coordination mechanisms that the humans use in order to generate a well performed motion. There are two numerously visited paradigms which defend different positions to that regard. The "part-whole transfer paradigm" states that integration of single components of a motion can be bolstered if these components are trained separately and then integrated together. Several studies showed that separate practice of the joints in the case of tennis strokes (e.g. [42]) was successful to learn the tennis tasks, or at least as good (e.g. for a sequential tapping task [32]). Also, successful part-whole transfer results were shown in a video-gaming setup[49]. However, in [32], the task was a discrete sequential task, where movement and reaction times were evaluated, in opposition to [42]. In [49], the task's focus was on the end-effector (i.e. posture correctness was not of main interest) and demonstration of the whole trajectory/motion was always provided. In fact, this latter aspect is not of lower importance. Several authors believe that the correct realization of a motion requires of practice of the full motion (also known as "Task Oriented training" paradigm). For example, in [85] several experimental results are provided which demonstrate the null transfer of strategies used to learn simple skills to complex tasks. In [36] it is also suggested than only by demonstration of the complete complex motion, can the single "alphabet" characters be played in a senseful way to create a correct motion. The balance required between learning simple components of a motion and the complex motion altogether is of outmost interest for us.

The goal of this project is understanding how complex motions are learnt. More specifically, the aim of the research conducted is to understand how the feedback provided, both visual and/or haptically, can be used to learn a motion, exploiting the "Part-Whole Transfer paradigm". From the research conducted at Reinkensmeier's Lab in California [42], we have learned that a complex motion can be learnt from its components, better than from the practice of the whole motion, solely. Also, it is known from their experiment that an anatomical break-down of the motion to the motion corresponding to shoulder and elbow, separately, might bring more understanding and skillful practice of the task. However, it is not clear to us the importance of practicing the full motion after having broken this motion down to its components (e.g. shoulder and elbow motions of a tennis backhand stroke) or whether, conversely, it is enough with learning the single components of this motion to master the complete complex motion.

Can a complete complex motion be learned solely from its components?; is the research question we seek to answer in this work. For answering this question, first a complex motion was selected: rugby drilled lateral pass. This real-life motion requires five DoFs coordinated in a ballistic motion which propels the ball at a maximum speed in the moment of release. Normally such motion take more than 1 session of practice to master, when learning rugby. The motion can be learned, in a real training scenario by isolation of arm swing and forearm extension and pronation. Therefore, it is a good candidate to explore the secrets of complex motion's coordination learning, as well as a motion which, at least, meets the definition of Wulf [86] of a complex motion.

To investigate the aforementioned research question, we will use the results of Klein and colleagues [42], in terms of part-whole training paradigm. The use of an exoskeleton robot, ARMin V, will allow us for exploitation of the results of [42], by breaking the mentioned motion to the anatomical components of this one (i.e. upper arm and forearm motion, separately). The ability of ARMin V to provide separate haptic feedback to each joint (5 DoF) will allow us to investigate the feedback modality (visual or visuo-haptic) which improves the motor learning of this broken-down motion. Additionally, the design of the training protocol will allow us to discern the importance of training the complete motion versus only training its components. This latter question had remained unanswered from [42] and it is, to our opinion of big interest. This will let us add some information to the useful results presented in [32], [49] and [42].

Our hypotheses were four:

- ***H1***: Breaking down a motion to its components (specifically stated, anatomical joint-related, i.e. elbow and shoulder motions) will improve learning of the trajectory (in agreement with [42]) and improve the retention of this knowledge. The confirmation of this hypothesis would provide support for the "Part-Whole Transfer paradigm" as stated in [36].
- ***H2***: Visuo-haptic instruction of the anatomical components of a motion is better than only visual instruction in order to learn the motion characteristics. Specially, the addition of haptic guidance will help in terms of retention of this knowledge according to [21] and [52].
- ***H3***: Visuo-haptic recomposition of the single components back into a complete motion is necessary for learning the movement. This would be in line with studies such as [22] and [52] supporting the use of haptic feedback. More concretely, it has been found that the haptic feedback provided, both for teaching the simple components of the motion and the full-motion, enhances the learning of a motion, specially speed profile terms; and that also retention is positively affected.
- ***H4***: We hypothesized that sense of competence, effort and enjoyment will increase for the more guided groups, as well as effort will drop when guidance is provided. However, interest should raise for groups being more challenged, theoretically being less supported. This is also in line with other studies which investigated the effects of challenge[1]in learning [19, 20].

To test these hypotheses, 16 subjects volunteered in a behavioral experiment performing a rugby motion while training under the different strategies outlined before. The results are presented in the corresponding sections of this work. Since motor learning and motor rehabilitation search many research efforts [35][51]. Indeed, some authors hypothesize that motor recovery (e.g. after a stroke) can be a form of motor re-learning [46]. We believe that the results of this research might have a transfer to neuro-rehabilitation, providing therapists and engineers with guidelines to design new innovative neuro-rehabilitative therapies.

The rest of this report is structured as follows. Chapter two focuses on the methods followed to conduct the study. First the experimental setup is briefly presented. An explanation of different criteria to better understand the sources of complexity of a task is provided in the following section. A third section is dedicated to highlight the factors considered in order to design the experimental groups. The following part of Chapter 2 explains in detail the study protocol. Later the several feedback subsystems are outlined. To conclude the Chapter 2, the outcome measures selected and the statistical analysis applied to the data are introduced. The results are provided in Chapter 3. Hypothesis testing and discussions of the implications of the study are provided in Chapter 4. Conclusions and further steps are presented in the "Conclusion", Chapter 5.

[1]Following postulates of the "Challenge point hypothesis" [30], it was of our interest investigating the adequacy of challenge and skill level during the training.

2

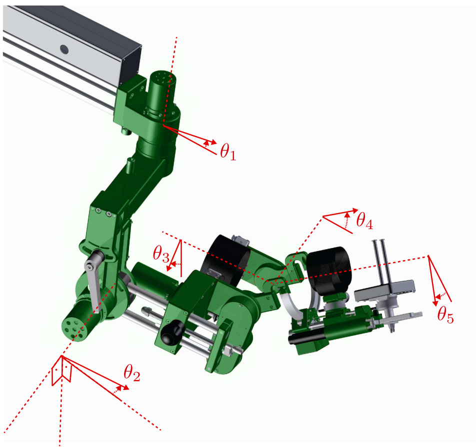
Study design and implementation

The research question tackled in this study was: *Can a complete complex motion be learned solely from its components?*. This research question was to be answered by understanding the role of haptic recomposition training of a broken down complex motion, on the performance of the full motion. The question was concretized by the hypothesis that anatomical training would facilitate motor learning and retention (hypothesis 1); that visuo-haptic recomposition is superior to visual recomposition of the components of a full complex motion (hypothesis 2); and that, visuo-haptic training is better than "visual only" training for speed profile learning (hypothesis 3). In order to answer this question, an experiment was designed, which took place at Balgrist Campus, affiliated with ETH Zürich. The apparatus, the design and implementation of the experimental system, the experimental design and the study protocol are outlined here.

2.1. Apparatus

The study was conducted at the Balgrist Campus within a research group of ETH Zürich, Sensory Motor Systems Lab. The device used for the study was ARMin V exoskeleton robot which was invented at SMS Lab.

For this study, ARMin 5 provided either haptic guidance or simply stayed in transparent mode in order to allow user's free performance.



(a) CAD schema of ARMin with the axis used in this thesis.

(b) ARMin V system in the experiment room.

Figure 2.1: ARMin V system used for the experiment.

ARMin V, is a 7 degrees of freedom exoskeleton robot (Fig. 2.1), which is used for rehabilitation. During the time period of the thesis, only the following five axes are used: shoulder abduction/adduction, shoulder extension/flexion, shoulder internal/external rotation, elbow flexion/extension and forearm supination/prosupination.

Axis #	Movement	RoM [deg]	Max. Torque [Nm]	Nominal Torque [Nm]
1	Shldr. Abd./Add.	$-120 < \theta_1 < 40$	59.5	10.5
2	Shldr. Ext./Flex.	$-40 < \theta_2 < 30$	82.2	22.4
3	Shldr. Int./Ext. Rot.	$-110 < \theta_3 < 0$	59.9	12.7
4	Elbow Ext./Flex.	$-110 < \theta_4 < 0$	59.5	10.5
5	Forearm Pro./Supi.	$-75 < \theta_5 < 75$	7.7	2.5

Table 2.1: ARMin V Range of Motion (ROM) and Max./Nominal Torque.

The arm of the patient is aligned with the robot through the lower and upper arm cuffs which are fixed to the respective robot links. The length of the upper arm and lower arm links of the robot can be adjusted and be measured using potentiometer signals.

ARMin V has 3 six-axis force/torque sensors (FTS), present in the hand, lower and upper arm; are used for acceleration control of the robot with the help of Disturbance Observers (DOBs) [62, 67], when it was in transparent more. In this study, only information of two of the sensors was used for control and measuring purposes. This is because only 5 joints are used (excluding the hand/writs motion) and the external control mode of the robot (from the therapist side) was not used. Some additional information which might help critical appraisal and evaluation from the reader is provided in appendix A.1.

The range of motion (RoM) and the maximum/nominal torques of the axes used in the thesis, are as in Table 2.1.

The robot was commanded by control algorithms implemented in an external target PC (xPC) with an installed real time operative system, i.e. OS, (based on Simulink Real-Time®). The communication to the host PC providing visual and auditory feedback as well as the research user interface was done via communication protocols based on TCP/IP and UDP implemented in the custom graphical user interface programmed in Unity3D called ARMin OS (developed at SMS Lab). The details about visual and auditory environments are provided also in this work. The control algorithms and different modes of control are explained in the corresponding sections of this work.

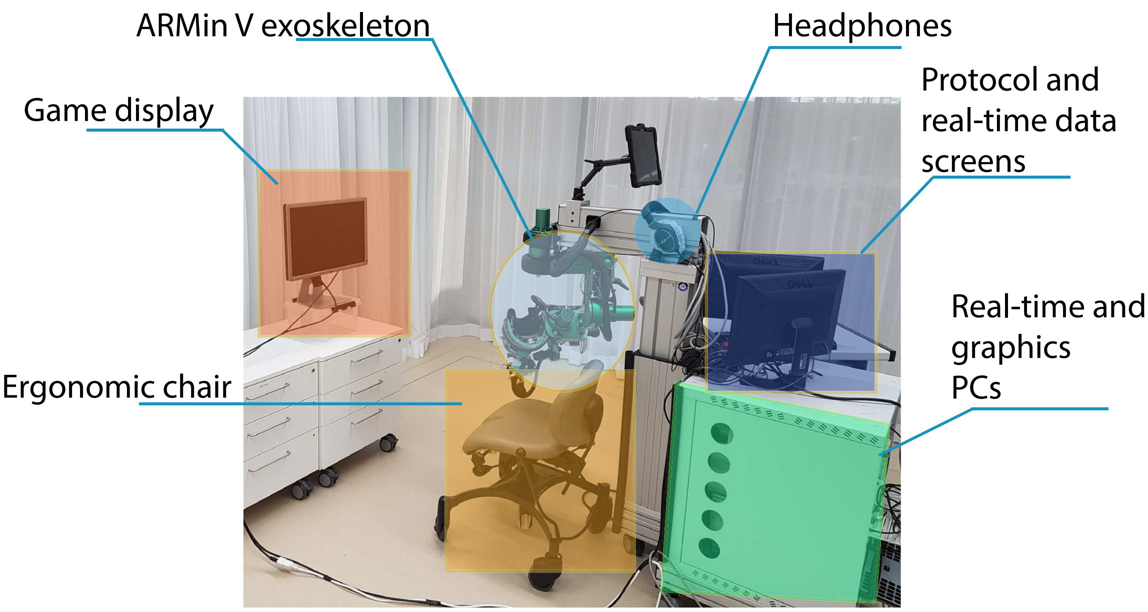


Figure 2.2: ARMin V setup: Experiment's configuration.

Finally, a 19" monitor was used for visualization of the virtual avatar and other training related information, as will be explained in the coming section. Also, an audio display (i.e. headphones) were used in the experiment as explained in detail in the following sections.

2.2. Selection of the motion

One of the challenges of this study was selecting a suitable motion, which would be complex enough to unravel the motion control strategies elicited by the volunteering subjects, but could be learnt in short time (i.e. 1 or 2 sessions) and be performed inside of the mentioned experimental setup.

The first problem, which I encountered in order to classify the motion used as complex is that complexity of a motion is not yet fully defined in the field. One of the most accepted definitions of "complex motion" is stated as follows:""[...]*although an exact definition of complexity is not possible, for present purposes, we will judge tasks to be complex if they generally cannot be mastered in a single session, have several degrees of freedom, and perhaps tend to be ecologically valid. Tasks will be judged as simple if they have only one degree of freedom, can be mastered in a single practice session, and appear to be artificial.[...]"*[86].

The aforementioned definition lacks concretization regarding the factors which define complexity. I have classified these factors, extracted from my literature research, as follows:

1. **Neural-computational challenges imposed:** Increasing number of degrees of freedom, a priori practice on the effective realization of the task, level of development and skillfulness of one's motor memory.

2. **Environmental noise:** Amount and compromise of feedback available versus feedback needed, potential existence or presence of (unexpected) disturbances, coherence of the feedback (stimuli) received.

3. **Aspects related to the task:** Refinement of the motions (i.e. accuracy required), amplitude of the motion, speed of the motion, compatibility of the motion to the anthropometry of the subject, and *naturalness* or as mentioned in [86] "ecologically valid" task.

4. **Skillfulness of the subject:** Level of development of kinesthetic and spatial intelligence [26]; and level of practice in a certain skill or movement. Note however the distinction between *functional task difficulty* and *nominal task difficulty* [30], where the last one reflects the difficulty of a task for matters related solely to the task (i.e. perceptual and motor performance requirements) and the first term relates "to how challenging the task is relative to the skill level of the individual performing the task and to the conditions under which it is being performed"[30].

Gabrielle Wulf[86] and Keith Hayes[34], among others, worked towards defining *complexity*, coming to different definitions. Based on differing criteria, it is difficult to classify motions as complex or simple when looking at real life scenarios, since there is a big component which relates to subject's skills level (see again [30] regarding *functional* and *nominal* task complexity). This is the reason why still the criteria of Wulf[86] was the main reference to define our reference task.

Indeed, Wulf mentioned [86] that in the field of motor learning, most of the tasks investigated so far are too artificial to assess motor learning in the necessary depth. Therefore, it would be useful to investigate tasks that have a direct relation to daily life and to find out if the research on simple tasks allows to draw also conclusions for complex tasks. For example, the following tasks have been studied so far: drawing[17], throwing darts[57][47], tennis strikes [52][42], rowing [74][66], among others.

However, there is a compromise between realism and resources made available for a study. Either the experimental setup is big enough and the motion can be reproduced realistically or with a certain resemblance to the real task as for dart throwing[76] or taichi training [77], loosing maybe other possibilities such as receiving haptic feedback. On the other hand, other studies which replicated the tasks in a smaller scale including inherent advantages, such as haptic feedback[42], but the tasks to not fully cover or do not resemble the real task. Not many researchers have managed to replicate with high fidelity a task (e.g. rowing [74] or tennis striking [52]).

To increase the knowledge in the field of motor learning of complex tasks and also due to the available hardware, we chose to investigate arm movements for a rugby pass inside an exoskeleton robot that is usually employed for rehabilitation training, i.e. the ARMin rehabilitation robot. For this reason, I put a big effort on thinking of a really challenging task, which would fit our experimental resources and facilities, but still be representative enough of what the task is. For this, I have followed guidelines related to ecological dynamics of learning [39] and also the common sense, as well an as thorough as possible level of knowledge of the already done studies in order to replicate good practices and avoid mistakes committed. Knowing also some other pieces of reference which define the motions according to their potential cost functions [60], the bio-mechanical principles which these one fulfill[43] or the type that they belong to (discrete or continuous, fine or gross, etc.)[71], helped designing and adapting the motion to the scope of the study. Finally, several feedback sessions with therapists, doctors, human movement scientists and other researchers from the department centered the decision. Some interesting aspects of this process will be briefly commented in the following.

For example, we critically reanalyzed the study of Klein and colleagues [42], where real-life (complex) movements and feedback strategies that enhance motor learning were in the focus. Specifically, we were interested in understanding whether breaking down of a complex movement (into single components of this one) effectively helps motor learning and to which extent instruction of the entire movement was important. Additionally, we were interested in which extent haptic feedback was important for effective motor learning in such a context. From that point on, the motion of the experiment of Klein was analyzed, simulated and finally replicated in our system. After seeing and analyzing that motion (i.e. position and speed profiles), as well as a visual understanding, several factors were not satisfying to us:

1. Limited amplitude and speed of the motion. Probably limited by the performance of their system and the practical/safety convenience of this. See comparative graphs (fig. 2.4).

2. Limited similarity to the real motion (tennis stroke or front swimming crawl). The motion used in [42] was generated after an equation whose parameters were tuned to resemble a real tennis motion, reducing the level of naturalism of the motor pattern.

3. High similarity between test and transfer motion investigate. This makes more feasible the transfer of motion and limits the strength of a potential finding in transfer of skills.

4. The low number of degrees of freedom (only 4, notice in fig. 2.4 the pronation-supination values for Klein et al.). Having the possibility of using up to 7 DoFs, in ARMin, (because more DoFs were used, see previous references to [86]), it was considered from the beginning the augmentation of difficulty of the task by increasing its DoFs (because more DoFs were used, see previous references to [86]).

For this reason, and with the goal of obtaining more gainful understanding of the human motor control strategies, the requirements were set, as follows (comparatively to Klein's motion [42]):

- Higher amplitude of the motion. See comparative graphs (fig. 2.4).

- Realism of the motion pattern.

- Substantially different target and transfer motion. In the target motion a lateral rugby drilled pass was trained while transfer was studied with a forward rugby drilled pass. Bot motions of Klein's study [42] studied movements whose main motion was a frontal abduction of the shoulder and extension of the elbow (i.e. tennis backhand and frontal crawl in swimming).

- New sport or task which has not been investigated, but which is still an upper-limb ballistic discrete motion (to resemble Klein's motion).

- More DoFs than 4(5 DoF, notice in fig. 2.4 the pronation-supination values for our motion, colored). At least include forearm pronation-supination.

- Recorded motion (from an experienced rugbier).

The rugby drilled pass, in two variants (frontal and lateral) was selected as a motion. This motion, has a couple of difficult points to master: the final pose of the forearm has to be parallel to the body of the athlete (in the lateral pass) or completely co-linear (in the frontal pass); at the same time that a sufficient spin and final linear speed are impressed onto the ball keeping the coordination timing of the elbow extension in phase with the shoulder adduction and forearm pro-supination. To learn the two aforementioned points (i.e. forearm orientation and spin), in the real scenario, the coaches tell you to train separately the spin-elbow extension complex and the arm swing. This possibility to separate the motion into its components, for the research question posed for this project, was of utmost interest to us. Additionally, the coordination pattern and kinematic features of the target and transfer motion differed substantially (in terms of maximum speed attained and Range of Motion, i.e. RoM, of each of the joints involved in the motion), both by visual inspection of the movement in the experimental setup and in the offline plotted graphs of the motion. Rugby is a sport which has not been widely investigated (only in terms of Virtual Reality and immersion [56] or behavioral aspects [14]). For all these reasons, the rugby motion was selected as presented in fig. 2.3 (see fig. 2.4, for

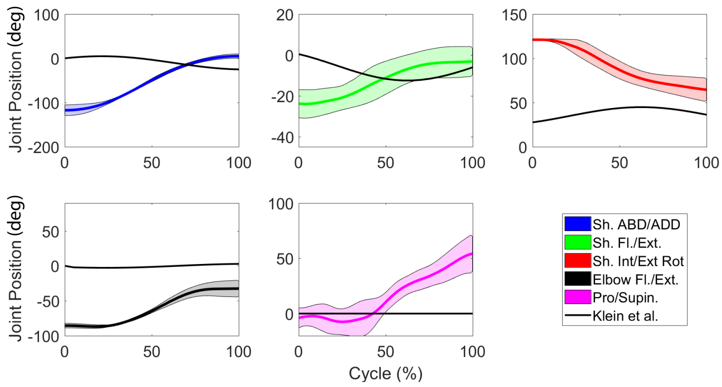
Figure 2.3: The rugby lateral drilled pass includes motions of 5 axes with a big RoM. Additionally, it includes some of the principles of bio-mechanics references in [43] (e.g. spin, coordination continuum, optimal projection, among others). These, among other factors (such as number of DoFs, etc.) are source of complexity for this particular motion.

more detailed understanding of the motion). Additional to the main motion, i.e. the lateral rugby drilled pass, a transfer motion was investigated (i.e. frontal drilled rugby pass, as mentioned above), in order to analyze the transfer of the learned skills to a similar movement.

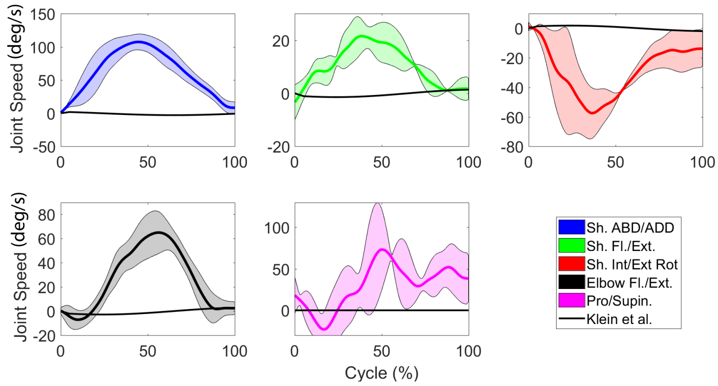
Another reason to study a throwing motion, was the scientific evidence which speaks for harmonization of "part-whole transfer" paradigm and "task-oriented training", such as [36] or [78]. Specially, the second reference was a strong scientific evidence supporting such a motion and a training based on the joint domain for our study. This second study concludes that a big part of the success of a throwing motion, relays on the correctness of the developed joint motions. This means, that also by training the joints, improvements in the end-effector motions can be found. The findings of this paper conditioned also the election of the coordination metric as a potential measure to validate the mode of learning (internal focus on joint motions or external focus on the trajectory shape) that the subjects used to achieve in the task. In other words, we aim for checking whether they improved in the coordination by learning from the joint based training or whether they merely improved in the trajectory of the arm by focusing on the whole motion.

Three conditions were analyzed: Training by means of full motion or anatomical training, visuo-haptic or visual feedback and visuo-haptic or visual full motion training. These conditions were assigned to different groups as presented in section 2.3. In other words, the goal was mainly to find out if training of the whole movement in addition to training the movement broken down as single joint movements is better than training single joint movements only.

Additionally, other aspects such as the effectiveness of haptic/visual feedback were assessed.



(a) Joint angle time-series values along the full cycle of the trajectory for each anatomical joint. Solid lines represents the mean values across eight trials recorded from an experienced rugby player. Filled area symbolized the standard deviation of the values for the 8 repetitions for the mentioned subject, giving an idea of how repeatable the motion is. In black the motion used for the study of Klein et al. [42]



(b) Joint speed time-series values along the full cycle of the trajectory for each anatomical joint. Solid lines represents the mean values across eight trials recorded from an experienced rugby player. Filled area symbolized the standard deviation of the values for the 8 repetitions for the mentioned subject, giving an idea of how repeatable the motion is. In black the motion used for the study of Klein et al. [42]

Figure 2.4: Motion characteristics: Comparative to Klein et al.'s motion. The motion has wider amplitude in position and speed magnitude. Also, it can be noted that motion's goal is to have a maximum spin speed, in a controlled manner (i.e. non-zeros final pronation and internal shoulder rotation speed). Additionally, the relative timing between shoulder and forearm movements is rich in timing, as profusely commented in section 2.6.1. In the figure

2.3. Group design

As already mentioned in this chapter, the goal of this thesis is understanding the role played by visuo-haptic recomposition of a complete motion when learning a new motor skill. To our intuition, in Klein's study [42], the role of full motion teaching for all the groups, was a reason for the good performance in terms of motion correctness. Probing this fact, is the main goal of this thesis. Probably the anatomical breakdown of a motion intro sub-components is, indeed, beneficial, as stated in [42]. However, a question remains open: Might it have improved the performance the fact that the full motion was displayed haptically too (and not only visually)?. Therefore, we hypothesize that it is important to visuo-haptically showing the complete motion in addition to breaking down the motion anatomically. Breaking down a motion anatomically, thus, might not be enough as enunciated in the title of [42], but recomposing plays an equal if not more determinant role.

The research question (*Can a complete complex motion be learned solely from its components?*)was concretized by three hypotheses, which were solely related to motor performance[1] (corresponding to the experimental variables, as represented in fig. 2.5):

- **Hypothesis 1:** Anatomical training in addition to training the entire movement facilitates motor learning and retention, better than training the entire movement only.
- **Hypothesis 2:** Visuo-haptic training is better than visual only training. Specially speed profile learning is benefited, as in [52] and retention should improve, being haptic information more persistent.
- **Hypothesis 3:** Visuo-haptic recomposition is superior to visual recomposition of the components of a full complex motion during learning and retention .

And these hypotheses were tested based on comparison in performance of the following four groups (fig. 2.6)

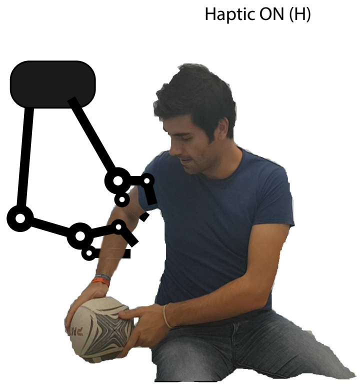
- **Group 1:***Whole coordination training*: Received full-motion visuo-haptic training during the whole practice session (in fig. 2.6 referred to as "haptic whole training and haptic recomposition").
- **Group 2:***Anatomical coordination training*: Received anatomical focused visuo-haptic training most of the practice session and one (visuo-haptic) demonstration of the full motion per practice session(in fig. 2.6 referred to as "haptic anatomical training and haptic recomposition")
- **Group 3:***Anatomical haptic training*: Received anatomical focused visuo-haptic training most of the practice session and one demonstration of only visual full motion training per practice session (in fig. 2.6 referred to as "haptic anatomical training and visual recomposition").
- **Group 4:***Anatomical visual training*: Received anatomical focused only visual training during the whole practice session (in fig. 2.6 referred to as "visual anatomical training and visual recomposition").

A good reason for keeping two of the groups already used in [42] is the potential of building on top of Klein et al.[42] results, but on a different (more complex) movement. However, the results of Klein et al. need to be replicated on the chosen movement. If this occurs, the other hypotheses (i.e. hypotheses 2 and 3) presented could be tested to expand the knowledge previously gained by Klein.

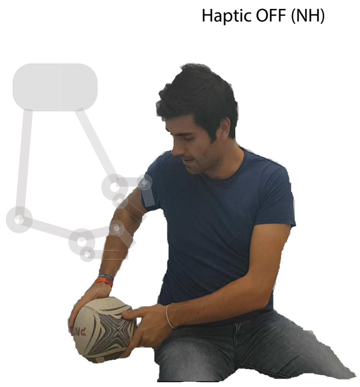
Additionally, the experiment could complement the implications of [42] for the advancement of this field. For example, this study could clarify the importance of full-motion haptic guidance after learning the broke down motion, for motor learning. The confirmation of this aspect, could help harmonizing the knowledge on the field regarding "Part-Whole Transfer paradigm" and "Task Oriented Training paradigm" as presented in the introduction, which is the main reason which speaks for addition of group 3. The group 4 was added for two reasons. First, the authors recommend in the discussion part of [42], inspect the influence of haptic or visual de-composition (i.e. breakdown). Also, the practical implications of group 4 being enough, for motor learning could be very positive; specially in the motor rehabilitation field. This could imply that virtual reality systems (such as [3]), could be sufficient for motor rehabilitation, and that systems such as [77] would be enough to train a sportive skill. This last step would be possible after replicating this study with, for example, stroke patients; since this study was conducted solely with healthy participants.

To conclude the group design section, from results of [42], it is expected, that, shape learning (position error decrease) would happen to a bigger extent in anatomical learning, in comparison with full-motion training. Based on results from [22] and [52] it is expected that haptic feedback (in our case, visuo-haptic) would enhance speed profile learning. It can be hypothesized that coordination patterns would improve in the case of adding a full-motion visuo-haptic repetition, which would increase the knowledge of performance in a richer way (haptic and visually). Therefore, increasing coordinated performance and retention of this one as in [9]. All these gains, mentioned from the literature consulted, should stay longer in case of haptic feedback [52]. Learning gains of a given motion, hypothetically, would be fixated in a more stable way, and its components would potentially be consolidated in a more clear and accessible way. As a consequence, skillful practice of the components of a certain motion would transfer to skillful achievements when practicing another motion, in agreement with "Part-Whole Transfer Paradigm" (see [36]). In terms of subjective measures, haptic guidance is expected to improve the sense of more self-competence, enjoyment, less effort, according to [19]. However, keeping a challenging point would be beneficial for learning the task [69], and would trigger neural processes [48]. All these hypothesis about the potential outcome of this study are graphically summarized in fig. 2.6.

[1] Note that a fourth hypothesis was formulated regarding subjective perception of task complexity.

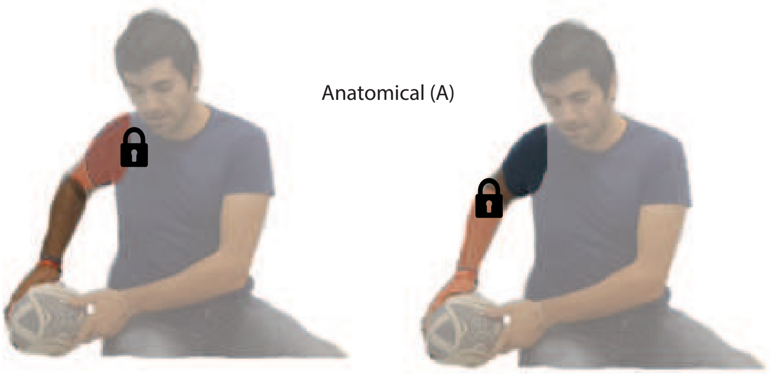


(a) The robot can be commanded to haptically guide the upper-limb of the users (similarly to how a real coach acts).



(b) The robot can be set up for transparent interaction mode. This is also referred to as visual only or transparent mode, in this work.

(c) The system can guide the subject (visually or visuo-haptically) during the full motion.



(d) The system can be set up for guiding the users in the motion of single joints while the other joints were fixed in a comfortable position (anatomically neutral[2]). The presentation of an *elbow* or *shoulder* motion was selected in a pseud-randomized way.

Figure 2.5: The combinations of haptic guidance and visuo-haptic guidance as well as joints involved in the training would produce different training scenarios here presented. While groups 1 and 2 would be provided with haptic guidance of the full motion in the last trial of each training round, this is not provided to groups 3 and 4, to test hypothesis 2, The inclusion of anatomical specific training in groups 2,3 and 4 would help answering the hypothesis 1. Group 4 is included, where the motion is trained only visually to answer Hypothesis 3.

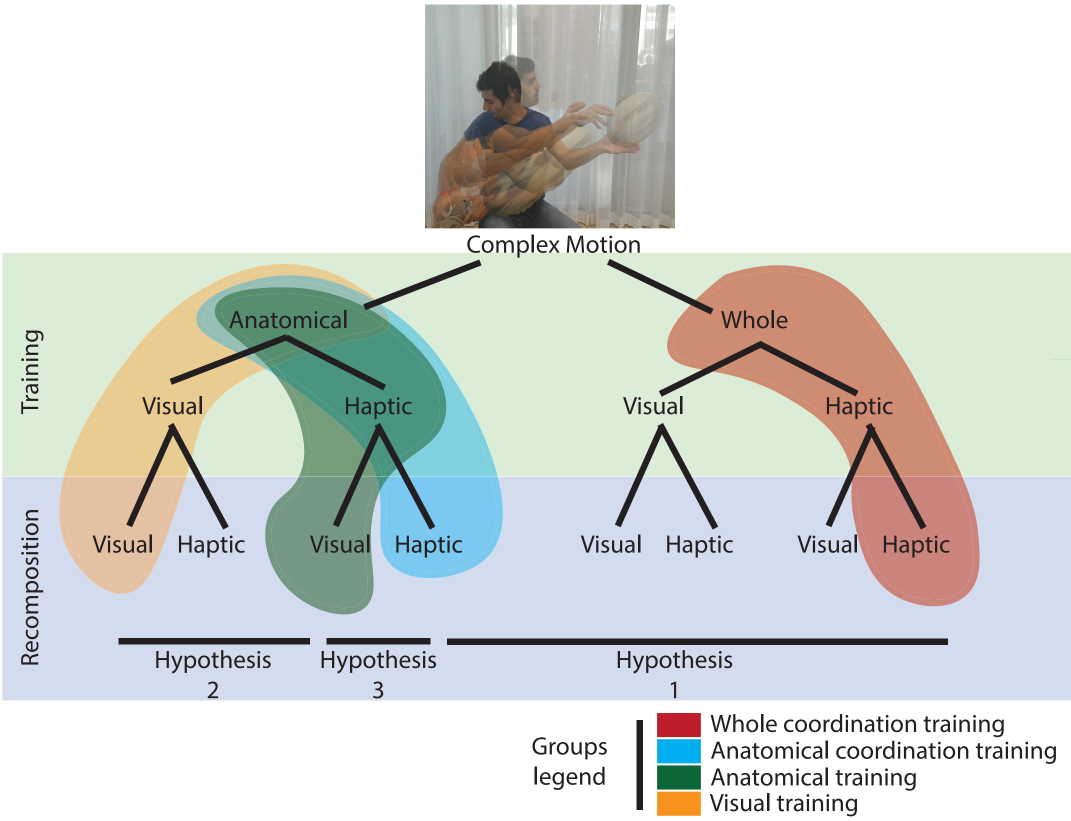


Figure 2.6: The different experimental factors can be combined in a factorial design. For practical reasons, to answer the three hypotheses mentioned in this section, only the highlighted groups have been studied. For clarification of the Training and Recomposition parts in this figure, please refer to the Protocol Workflow as presented in fig. 2.6. Please note the matching colors (i.e. green and blue). Note also that in this diagram only intervention conditions are sketched, i.e. only the training phase which was only provided for teaching of the target motion (lateral rugby drilled pass).

[2]Anatomically neutral was defined for us as neutral abduction, 90 degrees flexion and neutral internal rotation, for the shoulder. For the elbow, full extension and neutral pronation supination.

2.4. Study protocol

The study was run at the facilities of SMS Lab within the Balgrist campus in Zürich. The equipment used was mainly the ARMin 5 exoskeleton robot together with a screen and headphones to provide visual feedback and auditory white noise.

The study took place along the last three weeks of September 2017. A total number of 16 participants (11 males and 5 females, aged 20-31 years old) were recruited verbally among the workers of Balgrist campus and students of the ETH Zürich. Among the inclusion criteria for the study, right-handedness was required for participation (for hardware limitations of the system at that time). Also, naivety in the task, rugby pass, was required, so subjects were asked about their experience in the game of rugby. The latter was an exclusion criteria to take part in the study. Also, healthy vision or corrected to healthy vision was required, as well as no medical history of motor disorders or shoulder/elbow related pathologies.

The subjects conducted the study under the VIT-ARMin ethical approval issued by SwissMedic(clinical trial 2015-MD-0004 VIT-ARMin). All subjects provided signed consent for their participation and data storage and analysis.

In a preliminary estimation power analysis and meetings held at the *Statistische Beratung* at ETH Zürich it was found that, at least, 44 participants would be necessary. The effect size expected was an improvement in the joint motion tracking of at least 8 degrees, inferred from [42] for group 2 (i.e. winner). The other groups are expected to improve only 3 degrees. Standard deviation for the motion specified is between 3-4 degrees. With this a priori knowledge, GPower®was used to compute the sample size. An expected effect size of 1.571429 and a sample size of 11 participants per group resulted from this computations. The test used to get this estimation is Wilcoxon-Mann-Whitney model test. Finally, only 16 subjects were recruited for time limitations (derived from technical limitations). Despite this inconvenient, this study could serve as a pilot for a bigger upcoming study. Expanded recruitment by continuation of the study is considered at the moment, provided the results presented in this thesis.

All subjects underwent the experimental protocol in two sessions. The first session was dedicated to provide training. This first session was structured in three differentiated parts: Baseline, training and short-time retention. Both in baseline and retention, subjects received only visual feedback while being strapped into the ARMin robot in transparent mode. Visual feedback consisted of Knowledge of performance (in the form of visualization of two virtual avatars: semi-transparent one symbolizing the reference trajectory and solid one symbolizing the user's motion). Knowledge of results was provided in the end of the repetition in terms of trajectory shape error (the way how this metric was computed is presented in the corresponding section (in the following chapter , see section 2.6.1).

Before (each) Baseline, i.e. target and transfer motion practice, all subjects visualized video-explanations of the task they would face. This was to show them the task required without them experiencing the task, avoiding haptic display of this one, as in Klein's experiment [42] (see allocation of video blocks in fig. 2.7).

In both Baseline and Retention (both Short and Long-term retention, 1 week later) two motions were practiced: a target motion and a transfer motion; in order to evaluate the transfer of the acquired skills. See second rows in both Baseline and Short & Long-term Retentions in fig. 2.7 .

Baseline was 12 repetitions long (6 repetitions for target motion and 6 for transfer motion), of which 4 were test conditions were subjects were measured and received no feedback (just the own user's arm was projected in the form of a solid avatar arm). Only the score (i.e. error in trajectory shape, explained in section 2.6.1) was provided in the end of the test conditions with an indication of whether they improved or worsened with respect to the previous repetition. Short-term retention was 14 repetitions long (7 repetitions were dedicated for transfer motion), of which 6 were test conditions. Identical feedback and exercises were performed both in baseline, short-term retention (in the end of session 1) and long-term retention (in session 2). Long-term retention followed exactly the same protocol as short-term retention but only delayed approximately one week for each subject. Please refer to fig. 2.7, for a graphical representation of the protocol. Baseline and retention test were once executed for the target motion and followed by identically the same baseline and retention for the transfer motion, as presented in fig. 2.7, corresponded to the practice of transfer motion (frontal drilled rugby pass).

The training phase, as can be seen in fig. 2.7, involved ten series of practice blocks. Each practice block contains ten repetitions of which 8 are *training* repetitions (in green), 1 as *coordination training repetition* (in blue) and a last one as *test condition* (in red). Only the target motion was practiced during this 100 repetitions. The intervention is done in this training phase as follows for each group:

- **Group 1:***Whole coordination training.* The users assigned to this group, received during the 8 *training*

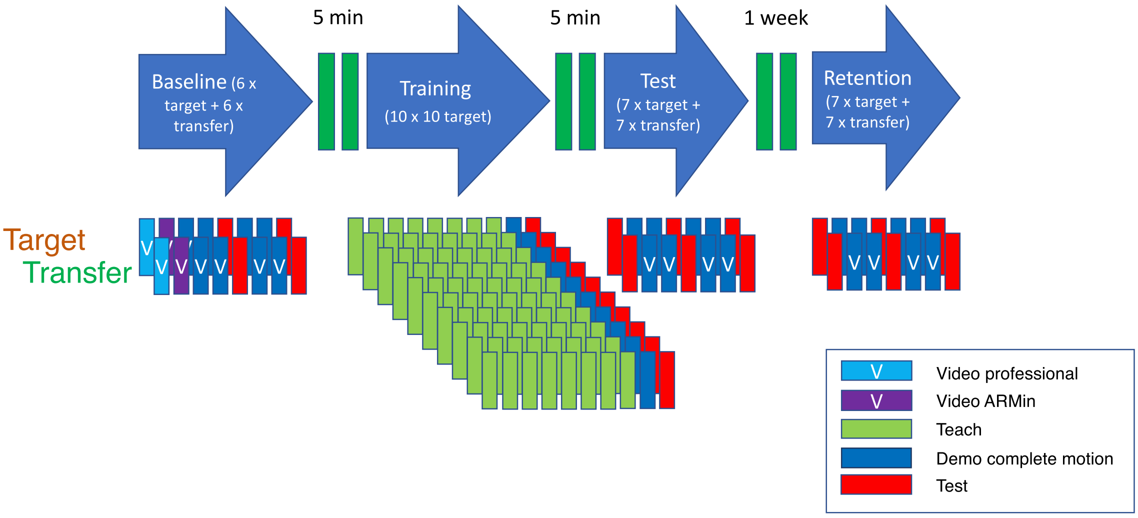


Figure 2.7: Protocol outline.

and the *coordination training* repetition the same intervention: full-motion visuo-haptic instruction of the target motion (please refer back to section 2.3 and figs. 2.5 and 2.6 for a deeper understanding).

- **Group 2:***Anatomical coordination training.* The volunteers in this group experienced during the 8 *training* repetitions a randomized visuo-haptic instruction of the motion, either on the part of the motion corresponding to arm swing [3]or forearm spin [4](i.e. anatomically specialized training). Later, in the 9^{th} repetition (i.e. *coordination training*, the motion was re-composed (from its components taught in repetitions 1-7) visuo-haptically with the help of ARMin 5 robot (please refer back to section 2.3 and figs. 2.5 and 2.6 for a deeper understanding).

- **Group 3:***Anatomical haptic training.* The practitioners of this group received also a visuo-haptic anatomical *training*. However, the *coordination training* repetition was provided just visually (please refer back to section 2.3 and figs. 2.5 and 2.6 for a deeper understanding).

- **Group 4:***Anatomical visual training.* This group received anatomical visual only training during both *training* and *coordination training* repetitions. For practical reasons, the exercises were still done inside of the robot in transparent mode (too keep a fair comparison under the robot dynamics) (please refer back to section 2.3 and figs. 2.5 and 2.6 for a deeper understanding).

All groups underwent 10 testing repetitions (i.e. the 10^{th} repetition of each practice block). Here, no haptic feedback was provided, nor visual feedback (i.e. reference trajectory was not provided, but just the own arm was projected), similar to the other testing repetitions happening during baseline or retention phases. Please refer back to fig. 2.7 for an overview of the protocol. The protocol transitions were automated, to ensure a correct randomization of the movements and other experimental variables. Subjects were provided with visual feedback, as can be seen in fig. 2.8b; while researchers could see the experiment realization status and variables in an interface , presented in fig. 2.8a, as well as real-time values of errors and position, as well as safety markers in a supplementary screen, as can be seen in fig. 2.2.

The presentation of each subcomponent of the motion was pre-randomized with a changing seed (done in MATLAB®) and stored on a file which was loaded for each subject. Still, the number of sub-components practiced over the full protocol was the same for all subjects. For practical reasons, the number of times

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

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

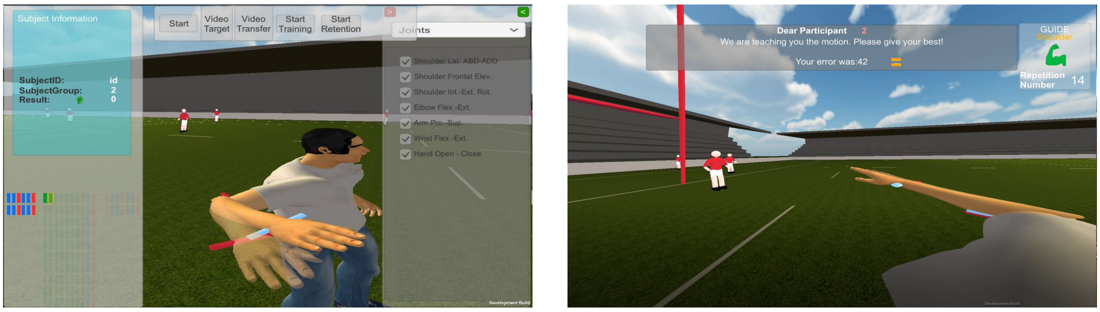
that each group practiced the full-motion, was obviously higher for group 1. This is commented in the discussion section. Assignment of the subjects to each group was done following a randomization made previously to the experiment start date. The randomization was done in blocks of 16 with the program on www.randomization.com[41]. Subjects were assigned to that randomized list in a first-come-first-served policy. For time constraints, as mentioned above, only the first randomization block was used (i.e. 16 subjects), given the fact that experiment was not continued for the 44 subjects planned (due to time and logistic constraints).

On-site experimental procedure

Before the first session, subjects who volunteered for the experiment had to fill in a screening questionnaire. In this way, the eligibility for participation could be confirmed.

A second interview took place in the beginning of the first visit. The subjects had to fill in the first part of the questionnaire, after general instructions about the experiment, the participants were presented to the ARMin robot and the safety guidelines were explained, as well as the safety measures implemented in the system, for their understanding of the safety standards.

Later, adaption to the subject's anatomy of the exoskeleton was done, fixing subject's arm onto the two cuffs (forearm and upper arm). After a brief final preliminary explanation and a get-to-know of the robot by the subject was held, the experiment was commenced. First, a video of the target movement was shown. On the screen, the participants saw a virtual scene of a rugby field a virtual rugby player (avatar), symbolizing the own arm. Then, the baseline of the target motion was started. Subjects were instructed to actively participate and try their best in following the displayed motion. At the end of this baseline, the video corresponding to the transfer motion was played. Subjects had time to ask question and, after, the second baseline for the transfer motion was started. After completion of the baseline, a rest of 15 min was given to remove numbness from limbs and for questions about discomfort and feelings of the subject.



(a) The researcher's interface was composed by two screens. One showing the real time data, in fig. 2.2, and another more elaborated interface to control the experimental work-flow and examine user motion strategies.

(b) The subject's GUI was presented on a monitor, in front of the subject that was seated and fixed to the ARMin robot, for provision of visual feedback and instructions.

Figure 2.8: Two screens were used for provision of different information, which was of interest for training (i.e. for the subject) or for monitoring (i.e. the researcher).

After the corresponding instructions: active participation and specific instructions regarding feedback modes, to ensure the understanding of the training from the subject's side; a new phase of the experiment started. In the training phase, each subject received the corresponding protocol defined for their corresponding group, as mentioned above. Subjects were allowed to make a break in the middle of the training phase (before practice block 6), after understanding the concerns of pilot study's subjects which complained about the shoulder girdle numbness (as documented in[58] with the limitations explained in [59]). After training, another break of 15 minutes was allowed. Then, the short-term retention phase started with a similar procedure as for the baseline, except without showing the videos. Then, the experiment was finished and another questionnaire, this time containing more questions and also the Intrinsic Motivation Inventory, to understand subjective performance-affecting parameters (such as effort, competence, etc.), which is explained in detail in the corresponding section. Then, the subjects would leave the research facilities until the second session (between 4 and 7 days later) were a similar procedure was followed for the long-term retention (retention 2) as for the short-term retention (retention 1). In the end of the second visit, the questionnaire used in the end of session 1 was provided too, including the IMI questions (see appendix A.5).

In the test conditions (in red), subjects were given additional chances (up to 3) in case they missed the trial for a lack of attention. For data evaluation, only the last repetition was taken. Subjects were not rewarded for participating but were kindly thanked for their support to this project. During the full experiment, volunteers were asked to wear headphones to avoid distractions (for more details on the auditory feedback see section 2.5.3. In total, session 1 lasted for 1.5 hours and session 2 for 0.5 hours. In fig. 2.9, a volunteering subject can be seen during the training.

Figure 2.9: ARMin V and participant ready for experiment

2.5. Feedback modes

2.5.1. Visual channel

The visual feedback provided to the users comprises of two elements: visual instruction and visual feedback. The second element can be separated into visual concurrent feedback and visual terminal feedback (also, *Knowledge of Results or KR*, in literature)

Preparatory visual instruction Visual instruction before each motion was provided also by video. The video consisted of two sketches with both professional rugby players conducting both motions and an experienced rugby player performing the action inside of ARMin 5. This was done for several reasons. First, in order to allow subjects imagining the motion. This would permit them to using motor imagery as a strategy which is intrinsically available to any human, facilitating transfer to the real scenario, in an ideal case[89]. All groups were exposed to this practice. Additionally, this visual demonstration allowed us to remove the overall haptic practice, provided in [42], whose contribution's understanding was the main goal of this paper.

Also, practice related instructions were provided in the upper right corner of the screen, in a symbolic intuitive graphical representation. See fig. 2.12.

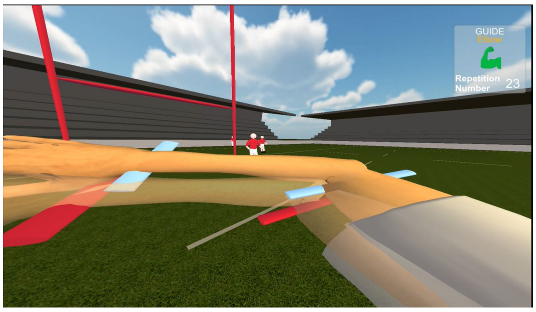
Apart from the visual instructions of the experiment, the researcher provided oral instructions, in order to decrease the cognitive load and the possible reactions to an un-expected intervention (e.g. robot haptic guidance initiated after a free motion). The information displayed, using color coding (red for tests when users were evaluated, blue for coordination training and green for training) and icons, related to type of motion, guidance mode and joint targeted (elbow or shoulder). Also, for practical reasons, and not to decrease the motivation for a long boring protocol, the number of repetitions conducted was displayed (allowing the user to know how much of the session was still remaining). In the required moments, before the testing and after each motion, information panels would pop up with messages (such as "move to homing position" or "This is a test trial, do your best"). Leaving a big part of the instruction of the users to the computerized protocol was done in order to keep a certain homogeneity in the instruction of the subjects. Also, to prevent excessive motion initiation delays (which could bias the data), the visual and haptic feedback (depending on the mode of training corresponding to the subject and phase) would be synchronized to start a motion only after a displayed count-down. This countdown could be reset if the subject would start the motion before the required time. Also, it could be re-started by the experimental assistant if required. These visual elements were meant only to not disturb the real intervention made in the experiment, which was the training; increasing the understanding of the subjects and allowing them to focus on what was important.

Visual feedback during practice Given the complexity of the task, most of the feedback was provided by visual and haptic cues. The complex parameters to be learnt (e.g. coordination of the joints, speed profile of each joint and range of motion or current angle of each joint) were offered in a concurrent fashion as augmented feedback and overlaid on a virtual representation of the subject's body (user avatar) with a solid texture. This avatar (and the subject, which was the master of avatar's motions) was meant to "imitate" the coach avatar (commanded by a trajectory generator, which took the motion from a library with the two recorded motions: target and transfer). The decision of using an avatar was taken based on the successful application of avatar-based learning for posture imitation, in the literature (e.g. tai-chi[77]). In this experiment, where Taichi was taught by a virtual avatar, learning of postures was enhanced by avatar usage in the first-person view (e.g. fig. 2.10), this was compared with demonstrations provided in third person view (e.g. fig. 2.11). Regarding our experiment, the provision of the information of the positions and dynamics (i.e. speed) of the motion was done in a concurrent fashion. Color coded cylinders were overlaid to the avatar texture (both for the reference and subject's postures, see e.g. fig. 2.11b) in order to provide the subjects with concurrent information of the error committed on the join angles (see fig. 2.10 and fig. 2.10c). By comparing the position, posture and time evolution of the latter; subjects could assess their errors while performing the motion.

Both avatars were generated with a software called MakeHuman®, in order to look as human as possible[5]. The avatars were imported in Unity3D and incorporated to the game scene. The avatars were rigged properly (with assistance of Blender®) in order to prevent singularities on the motion and to adapt their skeleton to the ARMin mechanical structure. For animation, a complete environment was created that would take either

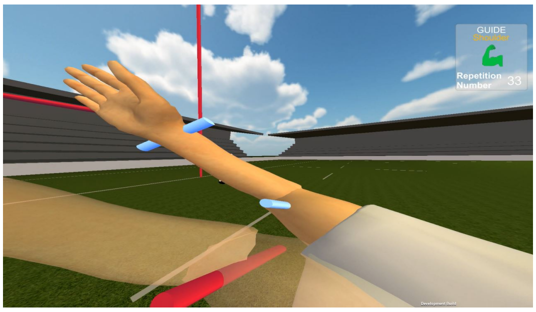
[5] In order to design the humanoid appearance of the avatar we have considered the reflections offered on [18], regarding the level of realism needed for acceptance of an avatar and Uncanny Valley theory.

the measured encoder data (for the user's avatar) or the generated reference trajectory (for the virtual coach) and use this information to command the motions of both solid and semi-transparent (ghost) avatars.



(a) First-person view allows more detailed joint position tracking.

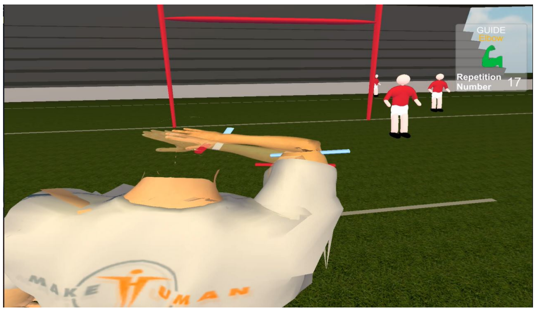
(b) First-person view presents two problems: spherical aberration/problems to render depth in a flat screen and field of view (FOV). These problems have to be circumvented (e.g. by moving the about Z axis).



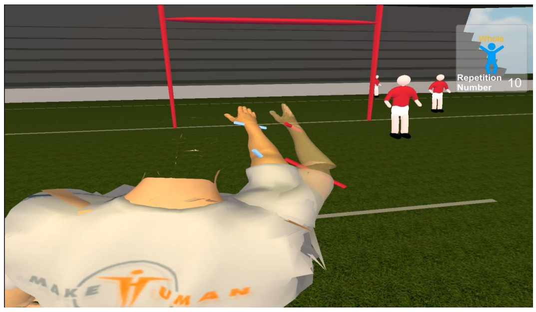
(c) Detail of the upper and lower arm posture in a first-person view.

Figure 2.10: The first-person view avatar was initially designed for a more realistic perspective. It was discarded, however, due to reported discomfort among several participants of the pilot testing.

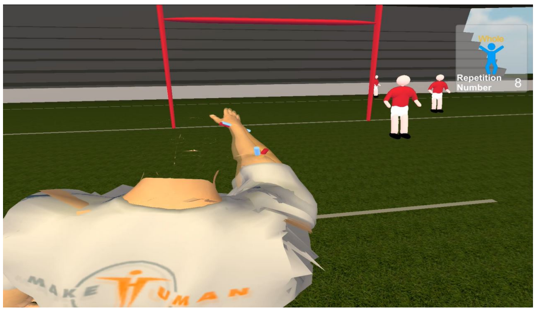
A full rugby scene was rendered to a certain point of realism. The initial possibilities to show this environment visually were two: first and third person view. The first-person view (presented in fig. 2.10) was achieved by placing a perspective camera (in Unity3D) at the position of the eyes of the virtual avatar. The orientation of this camera was linked to the rotation of the shoulder, in order to capture the full circumference of the arm swing motion. The alternative was a third person view (presented in fig. 2.11). The camera (also a perspective camera) was placed approximately a "hand" over the head of the avatar, lateralized to coincide with the clavicle of the avatar and protracted around "one arm" distance. This was done to center the arm swing in the center of the visualization and to be able to catch the full motion of the arm. The orientation was set to point forward, orthogonal to the shoulders-spine plane. Finally, the decision of adopting the third person view was done bearing the feedback received from senior researchers of the SMS lab (based on their previous experience on the field), and several pieces of literature versed on the topic of human avatars and visual perception[11][77][7]. The pros of using first-person view are a better performance on the shape of motion replication by using first-person avatars (fig. 2.10). On the other hand, first-person view avatars were used with head mounted displays, which made the display of all the joints conditional to the head motion of the user, which made the user miss some information. This was circumvented in our design by mapping the *virtual head* rotation to the shoulder movement (as if the user would always be looking at the hand, fig. 2.10c), even if the screen would be fixed. Discomfort reports (e.g. *cybersickness*) were received from several participants in the pilot testing, which discouraged us from using the first-person view. For this reason, the third person view was a good choice (see fig. 2.11). A small pilot study was conducted, with 8 healthy volunteers. Two volunteers were randomly assigned each of the four groups to test feasibility and allow an estimation of the group effects. These eight volunteers were called after the second session of this experiment to volunteer for 10 minutes more and complete the second retention of the experiment again, under first-person view. Results were gathered but for time limitations are not presented in this report.



(a) Third person view allows overall inter-segmental association, since a bigger field of view is covered.



(b) Big errors are easily perceived in a third person view.



(c) Appreciation of small errors in farther parts of the scene is more complicated in third person view, in comparison with a first-person view perspective.

(d) A wider range of motion can be covered without moving the camera, avoiding *vection* phenomenon and *cybersickness.*

Figure 2.11: Third person view avatars turned out to be more practical for our experiment.

Terminal visual feedback: Knowledge of results A second visual element was the knowledge of results, as in [42]. The mean absolute error of the position error (as explained in the corresponding section of outcome variables) was displayed only on the testing conditions (in red, i.e. when subjects were evaluated). Additionally, an arrow would encode the improvement, equality or worsening of the result in the current trial, w.r.t. the previous test condition. This information was presented seldom, only after test conditions, following guidelines contained in [86]. Also, the information provided was simple (error in position) and elaborated from the data, so that it would be beneficial for motor learning.

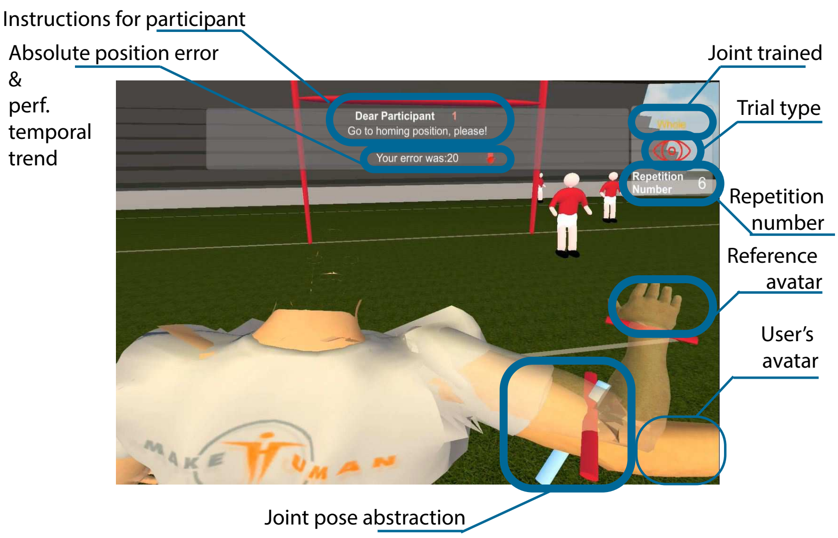


Figure 2.12: Visual interface for rugby practice

2.5.2. Haptic environment

The haptic feedback is provided via direct physical interaction with the ARMin robot. The interaction was made in two modes: transparent and guidance mode.

The transparent mode allowed users to move their arm freely. This effect is achieved by compensating the robot dynamics to a certain extent and, in our case, by using an acceleration observer with forces as an input. The ability of the robot to follow the user's movement is referred to as "transparency" in the literature(as stated in Ohnishi's Book: "*This ideal functional relation provides transparency: the operator feels as if he is manipulating the remote environment directly*" [62]). This behavior from the robot was achieved with the use of a Disturbance Observer (DOBs, see details in the Appendix appendix A.1). The DOB would provide a good estimation of the acceleration, which would steer a torque control algorithm to follow user's desired motion.

The other mode the robot was set up in was the guidance controller. This was basically a special variant of the DOB, in order to provide a PD control with a certain compliance, although in a stiff fashion. Eventually, the setup was equivalent to a PD stiff controller (for more information and tuning parameters, please refer to appendix A.1). This guidance mode was selected for two reasons: Replication of the conditions provided in [42] and literature evidence supporting the use of haptic guidance for the learning of speed profile of a motion. Haptic guidance has proven to decrease speed profile error (see[35]regarding convergent force fields or error reduction, depending on the author). Speed profile learning will be tested in our study by measuring the speed profile error (as described in the corresponding section 2.6.1). Additionally, as mentioned shortly before, the choice of PD instead of a force-related controller (e.g. admittance or impedance) was done according to the choice of the paper of Klein et al.[42], which was planned to be partially replicated.

The controller allowed the robot to follow a trajectory with a certain compliance. The stiffness of the interaction was fixed for a proper functioning of the system, for a comfortable interaction, and it was tuned for each joint according to the nominal inertias used by the DOB (for more information and tunning values, please refer to appendix A.1) . The trajectories which the robot would display, with the use of such a control law, were pre-recorded (instead of analytically generated [42]) and stored for retrieval and playback in the xPC-target in form of time-parametrized splines(as explained in fig. 2.14). The spline coefficients were fitted offline from recorded data of an experienced rugby player. This allowed for a natural reproduction of the motion.

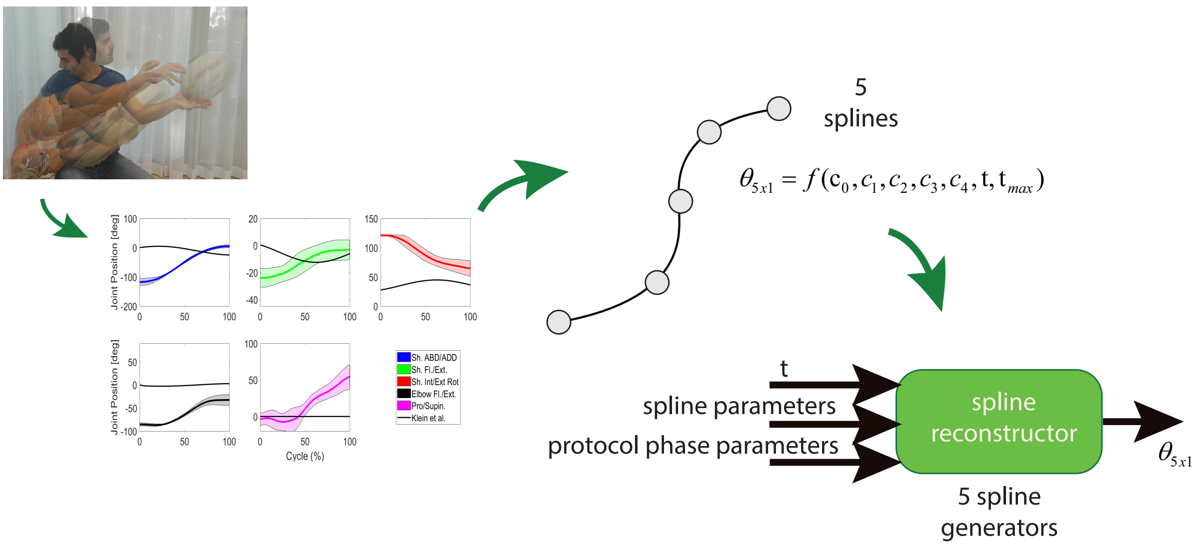


Figure 2.13: Motion is reconstructed from an expert-generated motion (e.g. a rugby player) in real-time. The motion re-constructor can be fed in with any recorded trajectory as soon as it is parameterized as a 5^{th} order spline.

The transparent and haptic guidance modes were alternated, during the experiment, in order to provide the users with the conditions show in fig. 2.6. In order to produce the experimental protocol presented later in this section, a supervisory controller was designed and implemented in the xPC, which was conceived to safely switch between haptic modes in a controlled and automated way. This supervisory control, running in Simulink Real-time®, was implemented in the State-flow®programming environment, on the xPC, and it presented two levels of organization. In the higher level of control, the experimental protocol with different phases and experimental conditions was represented. This layer allowed for transition between the three phases (i.e. Baseline, training and retention) and single trials within a phase corresponding to the training, coordination training and testing conditions, as will be presented in the corresponding "Study protocol" section). Also, the randomized corresponding anatomical subcomponent of the motion, at each trial, was determined and selected by this high level supervisory controller, and subsequently fed into the position controller. High-level flags such as repetition number, condition, phase, or trajectory presented were generated and communicated to the corresponding controller (e.g. position control for selection of trajectory) as well as the user interface (e.g. user interface for researcher or subject).

A second level of supervisory control was in charge of controlling the transitions between controllers in the single trials. This subsystem controlled the count-down, the elements being displayed, the control mode of the robot (e.g. transparent when the trajectory was finished or guidance, if required, while performing the motion) and the trajectories to be practiced presented in a randomized way. It was commanded by triggering signals giving information about the state of the single trials, with variables such as "inHome" or "endTrajectory".

These two-layer supervised and managed the PD control, feeding in the correct trajectory parameters (target or transfer motion) and enabling or disabling one or another via a safe fading trigger (also made for the occasion).

The design of the system was designed such that any transition on the experimental protocol could be executed and registered. Additionally, a full software-safety layer was set up to prevent and mitigate dangerous situations.

Inside of this environment, the subjects were guided or free to move across all the experiment in an easy to use and automated way; preventing possible experimental inconsistencies. Thanks to the partial physical compliance programmed for the haptic interaction, the subjects actively practice the motion, or conversely incur in errors (as shown in the graphics contained in appendix A.1).

Additionally, several measures had to be taken in order to ensure the safe haptic interaction between user and machine. For example, a workspace limitation was enabled, which was set up in the beginning of the experiment creating a safe box inside of which the user would remain safe, preventing the robot from penetrating its walls. Also, a maximum "towards the face" speed limitation was implemented, in order to push up the safety speed limits of the robot in not harming directions. This and other aspects are presented in the appendix A.2 with more detail.

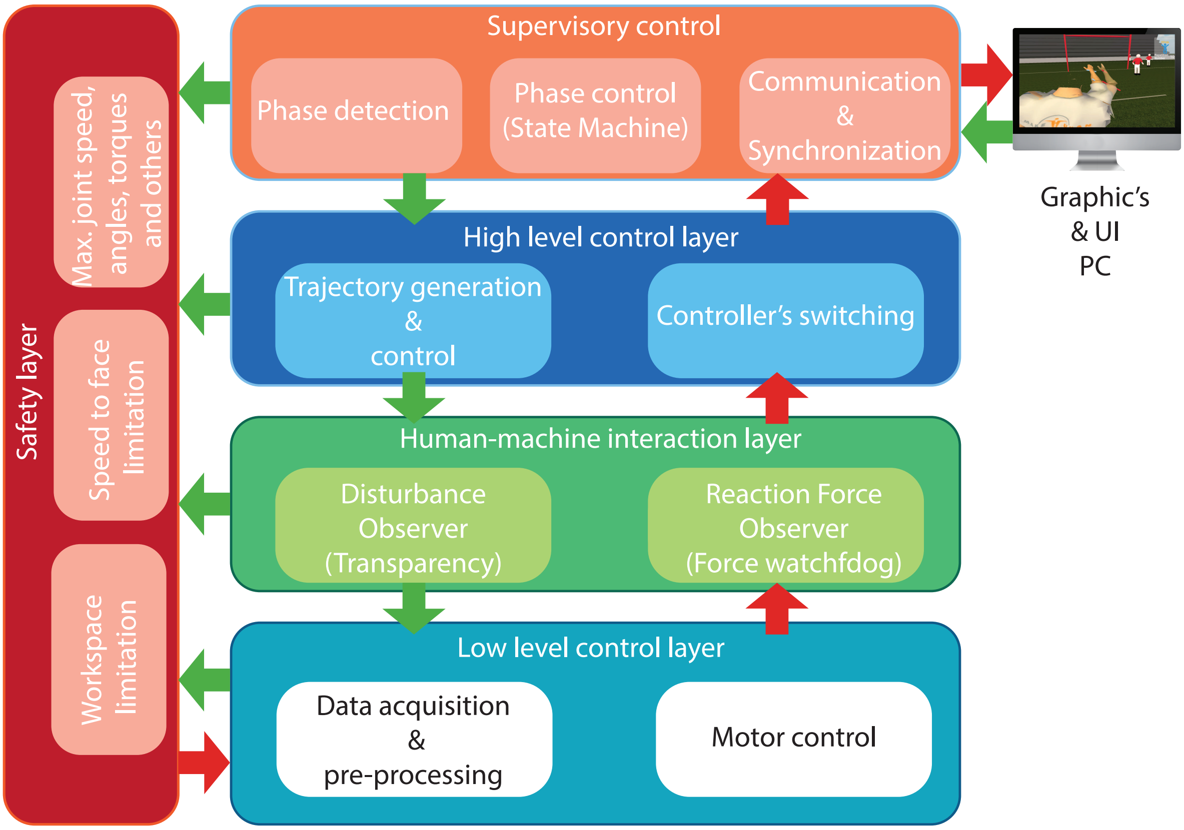


Figure 2.14: Multi-layer control system. Each layer interacts only with the adjacent neighbor interchanging interest parameters.

2.5.3. Auditory environment

Additionally, in order to control the auditory stimuli received by the users, a homogeneous and constant background sound was played on a pair of headphones that the subjects had to wear during the experiment. The sound corresponded to the background *white-noise like* crowd clamour at a baseball stadium.

The motivation of following such strategy was that studies prove that auditory feedback that is modulated in a way that represents speed can affect motor learning[65] [74]. In this experiment, due to the high dynamic demands imposed on the motion of the robot, the motors produced a relatively high noise that 1) would disturb and distract the subjects and 2) would be proportional to the speed achieved. For this reason, and to prevent any influence on the outcome due to unwanted accidental interventional effects (i.e. auditory feedback), a "white noise" like sound (namely a "baseball stadium" crowd noise, that would fit the virtual scene) was played. Sound was set up by the User interface but could be adjusted by the experimental assistant.

In the coming section, the way of how this subsystems interplay is explained.

2.6. Selected outcome measures

Several measures have been used to quantify motor learning of the subjects volunteering in the study. On one side, kinematic and dynamic parameters (i.e. position and speed errors) served to put number to the learning of the trajectory shape and speed profile. That is , how the trajectory looks at the eyes of an observer and whether it meets its functional goal (which is not directly evaluated in this report). The idea is that a motion which is closer to be correct, when compared to a *template* motion, should meet its function and provide a successful outcome. In our case, a correct speed profile and trajectory shape would propel the rugby ball in such a way that the pass would reach the receptor player, either on the left side of our subjects (in the case of the lateral drilled pass) or in the front of him or her (for the frontal drilled pass). As said, the "hit rate" of the pass is not evaluated, although it could be done based on certain parameters, which are defined in [43]. This will be out of the scope of this thesis, though.

A second part of the first section of this chapter is dedicated to the definition of coordination and the synthesis of a new outcome measure which it is used in this work. This, potentially, will provide us a better understanding of the cause of a correct or bad score on the two previous metrics. If these latter metrics were giving us a measure of the correctness of how a motion "looks like"; the coordination metrics will give us an idea of how correct it was performed, in terms of sequencing of motions of the different joints.

To conclude with the metrics used, the cognitive state of the practitioner while training a new task was also analyzed. For this reason, several items of the Intrinsic Motivation Inventory (IMI) were used.

2.6.1. Quality of the motion

The quality of motion was assessed in two parts: the output of the motion and how the motion was accomplished; being both equally important when assessing motor learning. In this part of the chapter, we will look at four parameters which help us understanding whether a motion was made correctly and resulted on a good motion pattern.

The selection of the metrics was done depending on the available data(i.e. kinematic data), the task targeted in the study (i.e. a rugby pass and its variant) and the related literature on the topic (e.g. [9, 42, 52]). The selection of this metrics was substantiated, after reading the recent review paper of Baron et al. [4].

In the outcomes section (chapter 3), the results will be show in three steps. First the time progress of the reduction on corresponding errors will be shown. Later, the comparison between the error level at each time stamp (between baseline and end of training, end of session 1 or short-term retention and end of session 2, i.e. long-term retention) are provided. Finally, a comparison of the results related only to groups representative of the three hypothesis (as presented before) is provided, to understand the correctness of each hypothesis on motor learning outcomes.

Also, all the metrics will be evaluated in terms of retention of the skill, as a difference between the end of training and the end of session 2. This is done in such a way because it is important that a learned skill persist on time. The transferability of the skills learned to another alternative motion (so-called, transfer motion) will be assessed, as well (with the time stamps of baseline and end of session 2). The importance of this two separate assessments (i.e. retention and transfer) has been missing in several studies (i.e. missing long-term retention in Feygin's study[22]). This has been acknowledged, though, by other authors, like Heuer[35], and therefore it is decided to include it in this work.

Finally, as a complement of the retention measurements, it is important quantifying whether there was an offline learning and its magnitude. This is referred to as "consolidation" in literature[63] and has been related to sleeping effects after skill acquisition [24]. It is here quantified as the difference in the error between end of training (when the intervention is finished) until the mean of the second session's errors (i.e. long-term retention), for each quality of motion's variables.

Since the rationale of the distinct outcome measures and tests has been explained so far, the following will be occupied with explaining the different data processing steps taken to make a meaningful use of the raw data , in order to obtain the outcome measures presented in this work. The specific statistical tests applied belong to section 2.7.

Data recording and pre-processing The data recorded during the experiment consisted of:

- Linear forces and torques applied in the sensors (raw filtered data).
- Projections of these forces onto the joints (joint torques).
- Position and speed of the end effector.

- Angles(θ_S) and angular speeds($\dot{\theta}_S$) of the 5 joints of interest (Shoulder Abduction/Adduction, Shoulder Flexion/Extension, Shoulder internal/external rotation, Elbow flexion and forearm pronation supination).
- Reference trajectory (θ_R) and speed($\dot{\theta}_R$) for the two desired trajectories (target and transfer) and the 5 aforementioned joints.
- Recording auxiliary variables to understand start and end of a motion, phase and sub-phase of the training, possible interruptions occurred and cause, number of repetitions (if it was the case) used in the test trials, condition used, time and day of the experiment, user id and group assigned.

This data was recorded from different sources (e.g. force sensors or encoders) at 1.8kHz. The data of the reference trajectory was generated online and differentiated in Simulink®. Post-filtering was done at 10Hz (Low pass no delay Butterworth filter) for the reference speed (due to a design mistake arising from an ill-defined spline which caused online discontinuity problems). Same procedure was followed for the measured speed (as differentiated from encoder data).

Later, the data was cut into singular motions for each trial and subject. The criteria defining the start and the end of the motion was being over or below, respectively, of a 10% of the maximum speed of the shoulder abduction/adduction or elbow flexion, for the reference trajectory. The data corresponding to the motion generated by the subjects was cut in the same way, but this time including the shoulder flexion. This was done to netter characterize the end of the motion (full-extension of the elbow). This off-line cutting of the data had to be performed in such a manner for a disregarded problem with the data synchronized "flags" used to signalize the beginning and end of the trajectory. This flags where not exactly synchronized with the data, for some real time problems occurring the target (xPC) running the controller when using Simulink Stateflow®. For a better understanding, please check section 2.5.2 and appendix A.1.

After obtaining each trajectory and speed profile for each of the 5 joints and for the reference and user's trajectories, the trajectories were resampled over the full trajectory cycle for each repetition (beginning 0% and end of motion 100%), in agreement with the previous criteria defining a full motion cycle. This was done in order to diminish or eliminate the effect of delays incurred in by the user (potentially after the end of the countdown). In other words, the reprocessed data contained real values of angular speed and angular position (for, both, reference and user's trajectory) but matched/resampled in the full cycle of the motion; so that we could compare the reference and subject's kinematic parameters at a given percentage of completion of the motion (e.g. the subject was 0.5 degrees per second below the required speed at 10% of the trajectory). Therefore, the time was scaled to a full motion cycle (note the X axis on all plots in this report). In order to resample the data, both positions and speeds (of reference and subject's trajectory) were fitted into a 5^{th} order spline, obtaining two arrays vectors (i.e. reference and subject) per magnitude (i.e. speed or position). For a better understanding, please check section 2.5.2.

After this pre-processing both speeds and positions, registered for the trajectory and user's motions were utilized in order to assess motor learning, as explained in the following.

Kinematic and dynamic features

In order to assess the goodness of the motion pattern generated by the subjects, position and speed error were selected as outcome measure. The reasons are several which advocate for selection of these metrics. Firstly, from robots, these parameters are easily accessible. In second place, the joints' positions and speeds can be used both for assessing the quality of motion at joint level, as it is the case in this study (since volunteers were trained also the in the joint domain) and can also be used (previous forward kinematics transformation) in order to assess end effector trajectories. This is not the case in this study, although the data could be later used in that direction if follow up works are conducted. A final reason for using these metrics is the popularity of this metric in the field of motor learning (e.g. [42, 53]). It has also been used in several robotic rehabilitation applications in order to measure quality of motion, too (see review [4]). Ultimately, the wish to partially replicate Klein's study [42], being able to compare the results, made easier the decision on the primary outcome measure.

Therefore, the first outcome measure consisted of the error between the reference joint angle's vector and the subject's generated trajectory (joint angles). It was computed as follows:

$$\epsilon_\theta = \left\| \frac{1}{F} \int_0^F \left(\theta_R(f_i) - \theta_S(f_i)\right) \mathrm{d}f_i \right\| \tag{2.1}$$

, being ϵ the average magnitude of the angular error. Being, also, θ_R the reference time series of angles and θ_S the subject generated angles. F is the full trajectory cycle (i.e. 100) and f_i is each cycle instant.

In theory, after our resampling of the trajectory, most of the error computed as in eq. (2.2) would measure the real mismatch between reference and subject's trajectory shapes, which can be due to magnitude or time lag errors, i.e. the shape of the trajectory.

This metric (norm of the mean absolute position error) gives information about the trajectory shape correctness, which according to our hypothesis would improve in the case of visuo-haptic feedback in comparison with visual feedback alone. It should also be better in the case of anatomically separated training of the motion, according to Klein's results [42]. This results will be presented later in this chapter.

Position error, as a metric to quantify trajectory's shape learning, is not enough, alone, when characterizing learning of a ballistic motion. For this reason, the secondary outcome measure to judge motor learning was the correctness of the speed profile generated. For that, the error was computed following this equation:

$$\epsilon_{\dot{\theta}} = \left\| \frac{1}{F} \int_0^F \left(\dot{\theta}_R(f_i) - \dot{\theta}_S(f_i) \right) \mathrm{d}f_i \right\| \qquad (2.2)$$

, being $epsilon$ the average magnitude of the angular speed error. Being, also, $\dot{\theta}_R$ the reference time series of angles and $\dot{\theta}_S$ the subject generated angles. F is the full trajectory cycle (i.e. 100) and f_i is each cycle instant.

The norm of the mean absolute speed error is used here in order to quantify how well or bad the speed profile of the reference trajectory was replicated. In theory, after our resampling of the trajectory, most of the error computed as in eq. (2.2) would measure the real mismatch between reference and subject's speed profiles, which can be due to magnitude or time lag errors, i.e. the shape of the speed profile.

The speed profile is hypothesized to improve with haptic feedback (groups 1 to 3), both immediately after training[22] and also in long-term retention [52], than visual feedback (our group 4). Theoretically, if should also be improved for anatomical training (group 2) more than for whole training (group 1), if the ideas of Bizzi and colleagues [5] hold. However, it could also happen that high frequency of practice of the full motion might be beneficial. This item will be clarified upon revision of the results. Also, it is expected that the speed profile improves more when haptic information of the full motion is displayed to the subjects (group 2) with respect to the condition were the full motion speed profile has to be gotten only from visual information (group 3).

Coordination of the motion

As presented before, one aspect that can be assessed of motor learning, is motor outcome (e.g. movement speed and shape). However, as pointed out by Cirstea and colleagues , this results could be even achieved under an incorrect motor coordination or muscle activation pattern[8], for example, in the clinical domain, by use of synergies [6] or by using other compensatory strategies (e.g. trunk rotations [8]). It is, then, a good strategy quantifying this faulty motor patterns and proposing corrective methods.

Not many authors have looked at the coordination patterns in upper-limb motion (see review [4]). In lower limb motion, gait analysis have provided a rich insight on the sequencing of bipedal motions to characterize healthy patters and disorders of the march. For example, Ihlen and colleagues [38] used generalized wavelet coherence analysis (GWCA) in order to quantify age-related ill-defined gait coordination patterns. This kind of analysis works well when the task is cyclic, presenting, thus, recursive features along the time. Based on cross-correlation of the datasets, this algorithm is useful to detect the level of harmonicity of the motor patterns of separated joints.

However, for the upper limb, there are more degrees of freedom [6]that interplay, and additionally, although depending on the task, in most cases, tasks are discrete (e.g. point to point motions). Other ways, less elaborated, of quantifying and characterizing motor coordination were proposed by Kelso and relate to either phase lag between joint angles [40] or in elaborated speed position graphs which can be used to predict stability of the systems, as for control systems theory[1]. Instead of using cross-correlation of several joints, Cirstea has come up with a new metric which expresses the inter-joint goodness of coordination. The Time-Coordination Index [9], is a calculated phase lag vector between shoulder and elbow angles, which has been used to quantify compensatory strategies initiated by stroke patients in rehabilitation. However, the adaptability of this metric for more complex motions where more than two joints interplay in order to let a complex motion pattern emerge has not yet been investigated.

[6]Not only knee, ankle and hip, but more non-colinear joints such as the three degrees of freedom of the shoulder, elbow and pronation

Additionally, related to another topic in the field (namely, training under external or internal focus of attention [88], i.e. focusing on the effects of the actions or in the actions themselves) it is the fact that coordination has proven to affect the outcome of throwing actions [78] which reinforces our interest in investigating such a parameter.

What can be taken from literature is an idea of what is understood by *coordination*. In principle, the relative angle sequence among different joints could be taken as coordination. A "correct" coordination has to be defined, then, with respect to a "pattern" or "template". For example, there is a more or less healthy way of walking [83] or batting a baseball[81]. Therefore, one can also define a correct way of making a rugby drilled pass. With this spirit and given the limitations of the approaches followed in literature (i.e. low number of degree of freedom [9] or rhythmic task [38]), a suitable metric was defined by the researcher team. This is explained in the following.

It is theoretically still possible, keeping a certain error in speed and position coordination without purely reflecting in an integral summation of errors (in position or speed) which might balance out or be affected by amplitude of the motion. For this reason, a coordination metric is proposed, which is two-folded. On one side, results are presented, quantifying the inter-joint proportion in joint excursion (i.e. the proportion or contribution of each joint angle to the overall pose). This metric is computed for each motion, each subject and all the groups. Finally, a goodness metric is compared by computing an error with respect to the reference motion. A second step is quantifying the error in transitioning from one pose to the next, which we have called dynamic coordination.

The coordination metric is computed, for position, similarly for reference and user's trajectory. First, the position (angles) time series vector (as formerly mentioned, resampled) and its offset is removed by subtracting from each value of the time series vector ($\theta^i_+(t)$) the overall mean (for that trial), resulting in only positive angle values. Later, the range of the motion is found for each joint (θ^i_{RoM})). Following, the percentage of contribution as each angle's value (each joint *i*) over the full scale of the same joint (eq. (2.3)) is computed. This says at which percentage of the maximum joint excursion is each joint (kind of a state of the current angles with respect to their overall ROM). The final step is computing the contribution to the overall pose for each time instant(eq. (2.4)). C^i results in a value between 0 and 1 which represents the level of "contribution" of the joint to the overall pose at time "t". The bigger the value, closer to 1, the more prominently the joint contributes to the motion in that instant, i.e. more overt is its position (closer to the upper maxima of its RoM). This gives a representation of the contribution(in magnitude) of each angle to the overall pose at time "t". In other words, is a picture that presents the level of excursion of each joint with respect to the overall "picture", for the subject's trajectory $C^i_S(t)$. See fig. 2.15. Similar computations are made for the reference trajectory $C^i_R(t)$. Therefore, two coordination metric time series vectors (5 dimensional arrays, i.e. one dimension per joint investigated) are obtained as a middle step for each trajectory.

$$\theta^i_{\%}(f_i) = \frac{\theta^i_+(f_i)}{\theta^i_{RoM}} \tag{2.3}$$

$$C^i(f_i) = \frac{\theta^i_{\%}(f_i)}{\sum_1^5 \theta^i_{\%}(f_i)} \tag{2.4}$$

As explained before, the correctness of a coordination pattern is assessed in a comparative manner to a *template*. Therefore, a last step is computing the error of user coordination ($C^i_S(t)$) with respect to the reference coordination pattern ($C^i_R(t)$). This was defined as pose coordination metric, show in fig. 2.15. Therefore, the first outcome measure consisted of the error between the reference joint angle's vector and the subject's generated trajectory (joint angles). It was computed as follows:

$$\epsilon_C = \left\| \frac{1}{-} \int_0^F \left(C^i_R(f_i) - C^i_S(f_i) \right) \mathrm{d} f_i \right\| \tag{2.5}$$

being $epsilon_C$ the error in pose coordination, obtaining the C metric for each test condition of the trial. Being, also, F full trajectory cycle, f_i each cycle instant and $C^i_S(t)$ and $C^i_R(t)$ computed as before. Results

of the forearm.

of this first metric is presented in fig. 3.1 across all trial's test conditions. These results are analyzed in the following

When differentiating in across the motion cycle the $C_S^i(f_i)$ and $C_R^i(f_i)$, two derivative vectors (with same 5 components) are obtained, which represent the transition between coordination patterns from time "t" to "t+1". This is named in this work as speed coordination or dynamic coordination (show in fig. 2.15). Apart of giving information on how the overall "photo looks" similar to the reference trajectory, in terms of joint excursion magnitude, we know now, additionally, the transition rate between motions, or how the coordination pattern evolves in time. An error is computed also on this time series, in order to assess its similarity with the sample correct dynamic coordination pattern, as follows.

$$\epsilon_{\dot{C}} = \left\| \frac{1}{F} \int_0^F \left(\dot{C}_R^i(f_i) - \dot{C}_S^i(f_i) \right) \mathrm{d} f_i \right\| \tag{2.6}$$

being $\epsilon_{\dot{C}}$ the error in dynamic coordination, obtaining the $\dot{C}$ metric for each test condition of the trial. Being, also, F the trajectory duration and $C_S^i(f_i)$ and $C_R^i(f_i)$ computed as before. Results of this first metric is presented in fig. 3.1 across all trial's test conditions. These results are analyzed in the following section of this chapter.

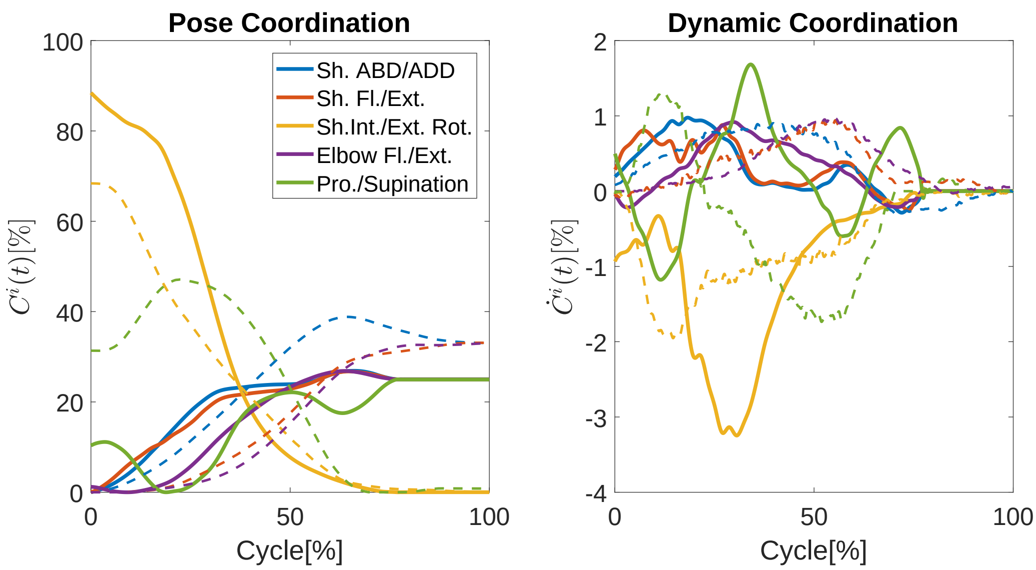


Figure 2.15: Coordination metrics (pose coordination and dynamic coordination) outcome for a given movement of a subject. Dashed line represents subject's performance, while solid line represents the required coordination pattern.

The dynamic coordination metric can be, for example, interpreted as explained in the following. In fig. 2.15 the coordination metric computed for a given motion of a subject is presented. At this specific motion, we can see the error committed by the subject (dashed line) in pose or static coordination terms, i.e. at the level of relative joint excursions (i.e. *openness* of the joint over the full possible range). Main errors early in the beginning of the motion (i.e. close to 0% cycle are the shoulder's smaller internal rotation, as well as bigger pronation of the forearm. While major pose of the upper-arm (represented by Sh. Abduction, Shoulder flexion and Elbow Flexion) are relatively correct. Around the 25-30% of the cycle, the shoulder should arrive close to final position in a progressive way (i.e. Sh. ABD and Sh. Fl.. For this motion, the error committed here was an over adduction, at around 40% of the cycle and a later shoulder flexion, which here was done in an incorrect synchrony with the Elbow Extension (instead of a lagged elbow extension. Also, see that the relative posture is quite distorted, with an imbalance between axial and lateral motions. This can be seen in a bigger excursion than required for Sh. ABD, Sh. Fl. and Elbow, causing excessive lateral motion, while the arm rotations (responsible for the ball spin) are not so big in magnitude and below required. This metric, as can be seen from this analysis, gives an idea of the shape distortion with respect to movement cycle, when computed as an error between a reference and a given trajectory.

If we look at the evolution of these angles during a cycle, we can appreciate in fig. 2.15, on the right-hand side (i.e. dynamic coordination), the cause of the pose errors. First, the wrong control of the axial movers or *spin-carrier* joints (i.e. pro-supination and internal-external rotation, is due to a lagged and excessive decrease in internal rotation and an anti-phase trend (inversed progression) in terms of pronation supination. This indicates that the coordination patter of the axial rotation component of the motion was not achieves in this motion for this subject. However, for the main contributing joints to arm swing (i.e. Sh. ABD , Sh. Fl. and Elb. Fl.) the motion progression was correct. Only a bit of lag produced an error in the final relative excursion, reflected in Pose coordination (fig. 2.15).

This metric provide both amplitude and timing related information which describes the features of a multi-joint movement with the particularity of relating joints among them.

Evaluation of the consolidation of the skill and transfer to a different motion

A side investigation of this work has been evaluating the consolidation of the apprehended skills and the transference of the skills to a similar motion.

Firstly, consolidation, is referred to as an offline learning and its magnitude [63] and has been related to sleeping effects after skill acquisition [24]. In this work is quantified as the difference in the error between end of training (when the intervention is finished) until the mean of the second session's errors (i.e. long-term retention), for each quality of motion's variables.

Additionally, transfer of the skills is measured, in this work, as the improvement between the Baseline and, both, Retention 1 and Retention 2, in the untrained skill/movement, i.e. frontal drilled rugby pass.

Both aspects will be quantified, and their results presented in the corresponding section. Our expectation is that the training strategy (i.e. Group) which has employed a better learning method (or metaphor) will show higher transfer and consolidation of the knowledge gained. Given the previous results of other researchers on the field, we expect that haptic feedback will improve retention of a motion [22], and therefore we suspect that consolidation is more intensively elicited in haptic trained groups. Additionally, we believe that a training focusing on the joints might give a more focused training of the motion which properly re-composed will produce higher learning. Therefore, the "Anatomical coordination training" group (i.e. Group 2) should show higher consolidation.

Also, a better consolidated "alphabet of movement primitives" [36], should provide a better transferability and ease to combine the primitives in new movements. Therefore, transfer of the learned skills should be more intense in the groups which were trained in haptic mode and specific training with focus on the joint (i.e. Group 2).

Evaluation of these two metrics will provide substantiation on the concepts of consolidation and transfer of the skills for the field of Motor Learning.

2.6.2. User experience

In the online pre-screening practiced for this study, questions relating personal background on motor skills, which could help understanding specific trends or observations on the data, were included. Naivety on the task was required, therefore subjects were asked to indicate whether they had played rugby before and at which level. Manifested skills in rugby practice was a strict exclusion criteria. Also, handedness was asked, for exclusion criteria reasons (i.e. the robot was only programmed for its use with the right arm, for time constraint reasons).

In order to evaluate the acceptance of the developed solution and investigate the user experience, the questions which were done (before and after each training session) related to how, subjectively, they found the different feedback items - i.e. after the experiment, the participants had to respond some questions about their user experience with ARMin and about the virtual environment.

In order to understand emotional impact of the presented training protocol on the subjects, the so called IMI questionnaire, was used. This questionnaire, which has been used in the past for motor learning experiments (e.g. in [19]), contains questions whose answer ranges from 1 (not at all) to 7 (very much). The instruments used of the IMI used were interest / enjoyment, perceived competence, effort / importance and pressure / tension.

For evaluation of the user experience a subset of questions from the widely used Intrinsic Motivation Inventory (IMI) ([54]), were used. The questions used, included in the appendix A.5, were also translated to German by a native German-speaking researcher. The subsets of IMI used covered the topics of interest and enjoyment(Q1-Q7), perceived competence(Q8-Q13), effort/importance(Q14-Q18) and pressure (Q19-Q23).

All study's subjective data were collected and managed using REDCap[7] electronic data capture tools hosted at SMS Lab at ETH Zürich. The full-questionnaire version can be found in the appendix A.5. The results after session 1 and session 2 (long-term retention) will be presented and analyzed in chapter 3.

[7] REDCap (Research Electronic Data Capture) is a secure, web-based application designed to support data capture for research studies, providing 1) an intuitive interface for validated data entry; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for importing data from external sources.[33]

2.7. Statistical analysis

After re-processing the data, as specified in the corresponding section (section 2.6), statistical analysis was performed to confirm or reject the hypotheses.

The primary outcome measure was the mean absolute position error, which allows for comparison with Klein's work [42]. The secondary outcome measures were: mean absolute speed error, pose and dynamic coordination and motivation and self-competence items, among others, represented by the IMI items explained before.

All hypothesis testing has been done in terms of *improvements*, e.g. decrease of error between baseline and the end of the training. This improvements were computed between baseline and the end of the training, the baseline and short-term retention and baseline and long-term retention. For Baseline, Training, Short-Term retention and Long-term retention, the average error of each phase (i.e. total of three trials) was computed and compared. The last 3 repetition of the training were averaged. These obtained improvements were normalized with respect to baseline performance in order to diminish probably effects of different levels of initial skills and to express the results as relative improvements.

The differences between baseline and end of training were used to assess all primary and secondary outcomes, while the differences between baseline and second session (long-term retention or baseline-retention 2) were used to assess retention of the learned skills. Differences between end of training skill level and second session dexterity were used in order to assess consolidation happening. Same procedures were used to assess the transfer motion (between baseline transfer motion skills and end of session 2). Similar procedure was conducted for the questionnaire data (IMI questionnaire) with the data between the end of session 1 and session 2.

Also, comparative testing were run to statistical ascertain the equality of data distributions on the start line (baseline performance), in order to discover potential significant differences in initial performances among groups.

In order to quantify a significant improvement (both in terms of quality of motion, i.e. error metrics, or Intrinsic Motivation Inventory items), attributed to an intervention, same statistical testing was performed. First of all, normality and homogeneity of the variance tests (Kolmogorov-Smirnov or Shapiro-Wilk and Levene's homogeneity test, respectively) were done in order to check for fulfillment of assumptions for parametric testing (e.g. ANOVA analysis). Given that not both of the assumptions could be ensured for all metrics and groups, non-parametric testing was conducted. For this, Kruskal-Wallis one-way ANOVA were used, in order to find significant differences between several groups.

Post-hoc testing(Mann-Whitney U-test) was used for mean comparisons of the different groups were performed, when significance would be close to $p = 0.1$ (when using Kruskal-Wallis one-way ANOVA). The only comparisons performed were for testing our hypothesis: Superiority of anatomical training (i.e. group 1-group 2) , superiority of haptic recomposition (i.e. group 2 -group 3), superiority of haptic training (i.e. group 3-group 4).

Significance level was set for $\alpha = 0.05$ for all tests. Results are shown for one-tailed statistics. Effects sizes, medians and quasi-significant comparisons are provided, too. Cohen's guidelines for effect size acknowledge a large effect is .5, a medium effect is .3, and a small effect is .1 [10].

The statistical software SPSS Statistics[37] and R[64]. The book [23] and the article [75] were used as guidelines for a correct reporting of the results.

3

Results

This thesis tries to answer the question of how motor learning of complex motions is affected in terms of "part-whole transfer" practical implications and haptic guidance effects. For quantifying or characterizing motor learning, several criteria have been used complementary.

In the remaining of the chapter, all this information is put together and applied to our dataset. The metric's results for each group and time frame of the experiment are analyzed and statistical power is reported.

The outcomes used to assess the effects of the intervention can be separated into motion related parameters and parameters related to the user experience and user "feelings". In the following, the results are reported with the corresponding statistical analysis.

Before stating the exposition of the results, please note that there were not significant differences in the initial performance or IMI scores among participants allocated in different groups, confirmed by statistical testing.

3.1. Quality of motion

In terms of quality of motion, it has been distinguished between kinematic and dynamic features of the motion generated by the user. As well, the coordination aspects are assessed in the section and properly reported together with the statistical results.

3.1.1. Kinematic and dynamic features

Two different parameters have been used to assess the quality of the generated motion, in first place, the position error is reported and lately the speed error results are given.

Position error metric In order to quantify motor learning, as it has been commented before, the improvement in terms of position error was quantified for all groups. The error improvement (i.e. decrease) has been computed as mentioned in the section 2.6 and is presented in fig. 3.1.

As a result, comparative statistical testing was performed across all groups and across all phases. The results of this improvement computation are shown in fig. 3.2 On this data, statistical testing has been performed in order to find significant differences among groups. Given the fact that data was of very heterogeneous characteristics across groups (e.g. missing data and high spread), a preliminary exploration for the checking the assumptions on normality and homogeneity of variance was performed. Kolmogorov-Smirnov normality test (and if necessary Shapiro-Wilk for more conservative considerations) and Levene's homogeneity tests were used. The results are summarized in the following Table A.3

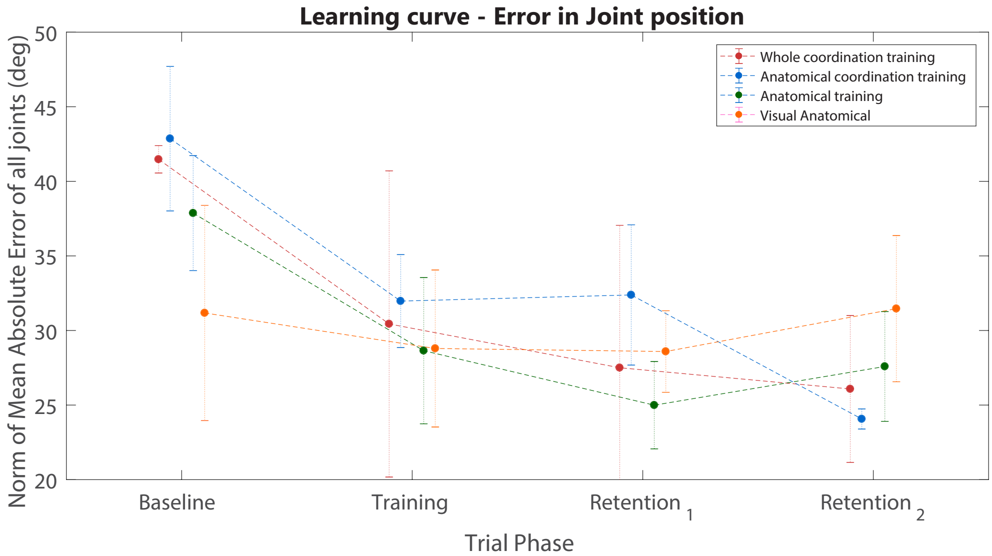


Figure 3.1: Evolution of the subject's error in position across trials. Bar graphs are used to provide the standard deviation. Mean performance (i.e. position error) is computed for the 3 baseline, early and late retention trials, as well as for the last 3 trials of the training phase.

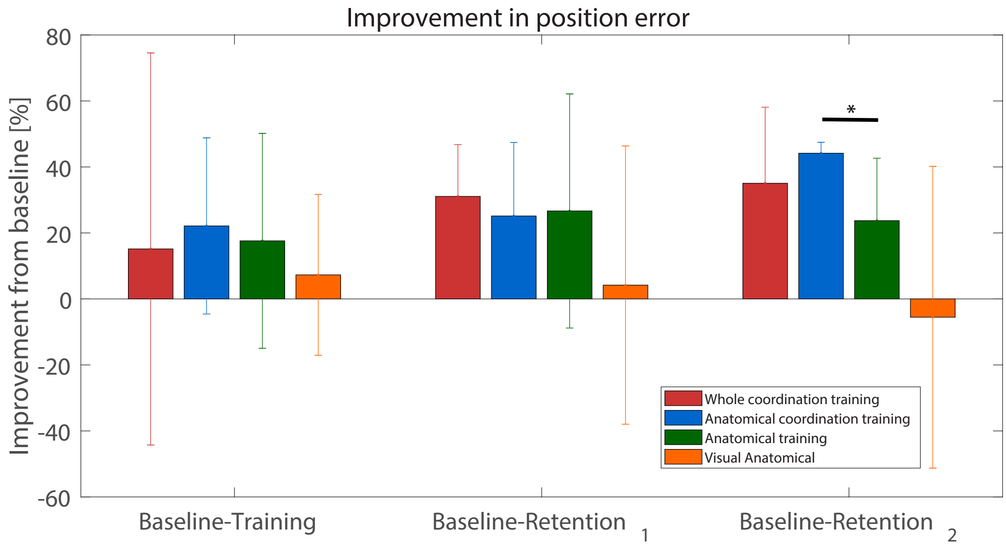


Figure 3.2: Relative improvement (w.r.t baseline performance) of each group in regard of position error. Comparative hypothesis testing among study design factors for movement shape learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. p<0.05 marked with *. p=0.1 is signalized with +.

As can be seen, not all tests pass the normality and homogeneity tests. Since at least one group in two of the time stamps violated the assumptions that allow for parametric statistical testing, non-parametric testing was used for all groups for this metric. Also, in order to confirm Q-Q plots were generated which confirmed the weak normality of the groups which passed the normality tests, which confirmed the suitability of application of non-parametric tests.

In order to detect potential inter-group significance a Kruskal-Wallis test was run for each time stamp. This test gave for the first time stamp (i.e. Baseline to end of training) a non-significant difference between groups); $H(3)=1.390$, $p>0.1$. Also, for the Baseline to Retention 1 time span no significant difference between groups was found; $H(3)=1.831, p>0.1$. However in retention 2, a marginally significant difference between groups ($H(3)=5.890; p=0.1$) was found. For this reason, each hypothesis was tested separately with pairwise testing (Mann-Whitney U Test). Results are shown in the following graphs (fig. 3.2 and fig. A.9). Group 2 (Mdn=18.25%) was significantly different from Group 3 (Mdn= 24.21%), $U=2.00$, $z = 1.732$, $r=0.61$ large effect, $p<0.05$.

Haptic Anatomical training and recomposition turned out to be in average better than visual recomposition, although not significantly (i.e. $p>0.05$), in the long run (i.e. approximately 1 week later. However, there is no significant differences between anatomical or whole motion training, as well as visual versus haptic training. Trends can be identified though, pointing out that group 2 (being trained with anatomical haptic decomposition and haptic recomposition) could outperform the other groups.

Speed error metric To complement the position error in evaluating the quality of motion, the speed profile learning has been quantified. The computation has been pointed out before and results across the experiment, for all groups are shown in fig. 3.3.

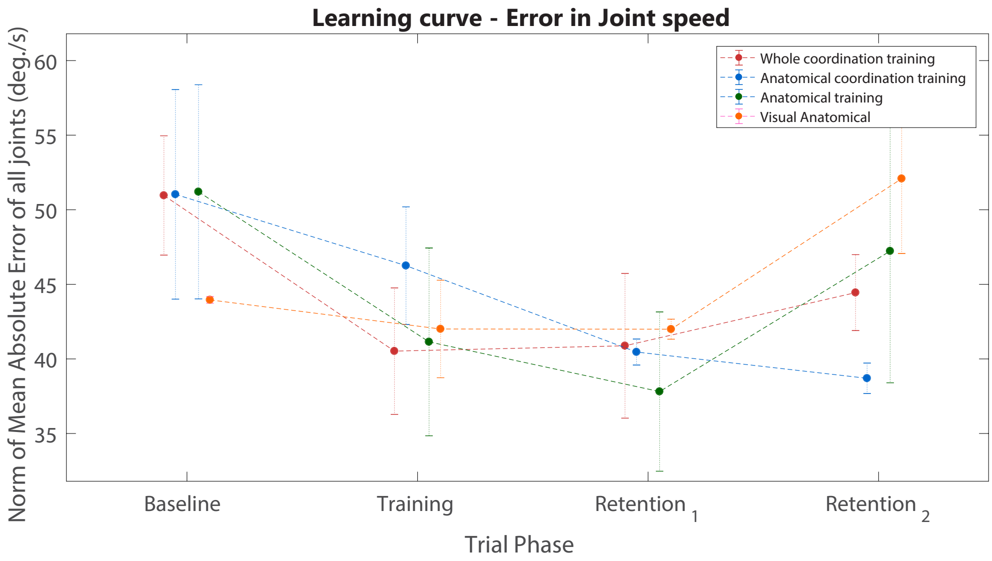


Figure 3.3: Evolution of the subject's error in speed across trials. Bar graphs are used to provide the standard deviation. Mean performance (i.e. position error) is computed for the 3 baseline, early and late retention trials, as well as for the last 3 trials of the training phase.

In fig. 3.4 the improvement in speed profile learning has been plotted between different phases of the experiment. The figures shown in fig. 3.4, as explained in the corresponding section 2.6, the data is normalized over the baseline error in order to standardize learning quotas regardless of initial user's skill level.

Figure 3.4: Relative improvement (w.r.t baseline performance) of each group in regard of joint speed error metric. Comparative hypothesis testing among study design factors for movement's speed profile learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. $p<0.05$ marked with *. $p=0.1$ is signalized with +.

Similar statistical testing as for previous metric was performed, regarding homogeneity and normality (which is included in the Appendix); and, given, generally, violation of these two assumptions, non-parametric testing was again conducted. Given the fact that no significance was found in neither a Kruskal-Wallis test (i.e. $p>0.1$, for all time spans) nor bar plots (i.e. visually) revealed potential significant differences among groups, no further pairwise comparisons were performed, opposed to beforehand. However, some trends can be seen in A.10. These trends suggest marginal superiority of joint separated practice (anatomical training) over whole practice in the long run, as in fig. A.10a can be seen. Also, an irregular comparative between haptic and visual recomposition fig. A.10b and, in average, a variably superiority of haptic versus visual training, in fig. A.10c. All in one, our group 2, i.e. haptic anatomical training with haptic recomposition might have a better retention of the gained knowledge, despite the lack of statistical power to back up this statement.

3.1.2. Coordination of the motion

Pose coordination metric The characterization of the static coordination or pose coordination has been reported before and results across the experiment, for all groups are shown in fig. 3.5.

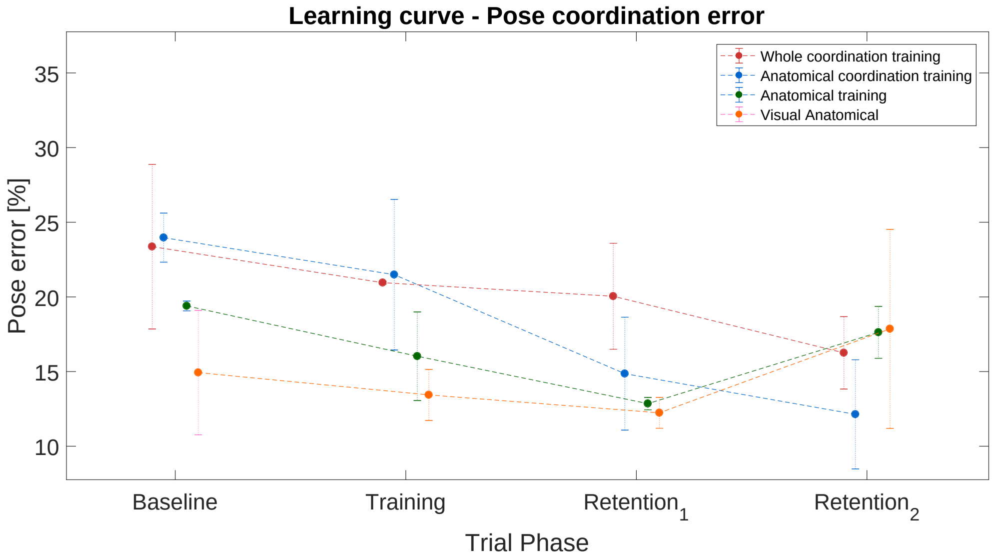


Figure 3.5: Evolution of the subject's error in position across trials. Bar graphs are used to provide the standard deviation. Mean performance (i.e. position error) is computed for the 3 baseline, early and late retention trials, as well as for the last 3 trials of the training phase.

A similar plotting as before, with three time-stamps across all experiment's trials is shown in fig. 3.6. The error improvement (i.e. decrease) has been computed as the subtraction of a time-stamp's error (e.g. early retention phase), from the baseline error and normalize over the baseline error in order to standardize learning quotas regardless of initial user's skill level.

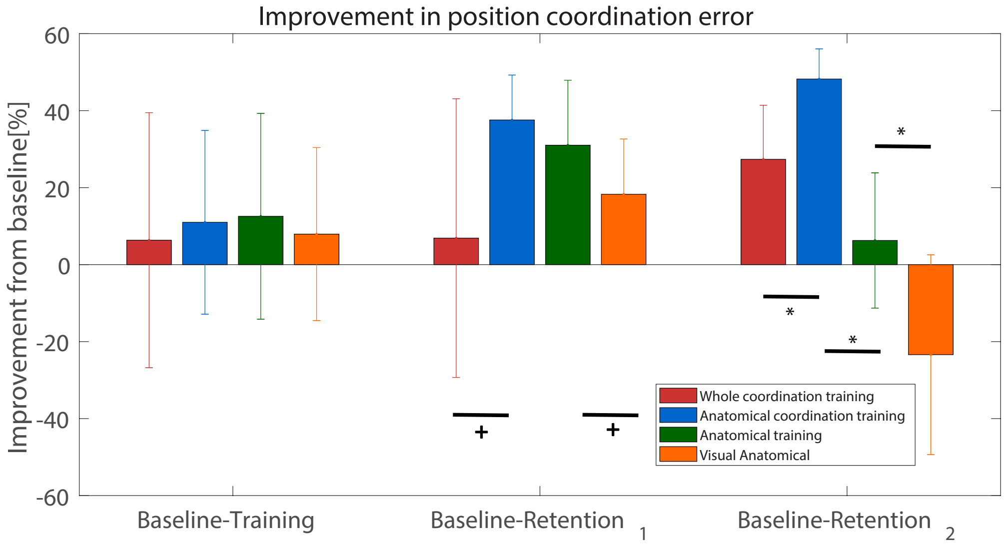


Figure 3.6: Relative improvement (w.r.t baseline performance) of each group in regard of pose coordination metric. Comparative hypothesis testing among study design factors for movement pose coordination learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. p<0.05 marked with *. p=0.1 is signalized with +.

Similar statistical testing as for previous metric was performed, regarding homogeneity and normality (which is included in the Appendix in Table A.7); and, given, generally, violation of these two assumptions, non-parametric testing was again conducted. Kruskal-Wallis gave for the first time-stamp (i.e. Baseline to end of training) a non-significant difference between groups); H(3)=0.243, p>0.1. Also, for the Baseline to Retention 1 time span no significant difference between groups was found; H(3)=4.257,p=0.235. However in retention 2, a significant difference between groups (H(3)=11.228;p=0.011) was found. For this reason, each hypothesis was tested separately with pairwise testing (Mann-Whitney U Test). Results are show in fig. 3.6 and the following graphs (fig. A.11).

Group 2, or the subject's who were delivered an anatomical-based haptic training with haptic recomposition, outperformed others, and haptic feedback demonstrated superior performance. As can be seen (fig. 3.6 and fig. A.11a), the full-arm training resulted not so effective for the subjects in the end of the first session (Mdn_1 = 15.70%) against anatomical-specific training (Mdn_2 = 37.17%) [U=3.00,z=-1.443, r= 0.52 large effect;p=0.07] . Also, a better retention is shown between group 1, Mdn_1 = 27.18% and group 2, Mdn_2 = 51.92%[U=1.00,z=-2.021, r= 0.71 large effect;p=0.02] . Haptic training showed a trend of being better than visual training, both in short (Mdn_3 = 29.15%; Mdn_4 = 24.04%) [U=4.00,z=-1.155, r= 0.41 medium effect;p=0.1] and long-term retention (Mdn_3 = 2.44%; Mdn_4 = −30.65%)[U=3.00,z=-1.443, r= 0.52 large effect;p=0.07] . Finally, it is, upon results, beneficial the haptic recomposition of a broken down motion, in terms of coordination on a long run(Mdn_2 = 51.93%; Mdn_3 = 2.45%)[U=0.00,z=-2.309, r= 0.82 large effect;p=0.01].

Dynamic coordination metric The characterization of the dynamic coordination or pose coordination has been reported before and results across the experiment, for all groups are shown in fig. 3.7. This metric gives us an impression of the correctness between distinct poses along a single motion.

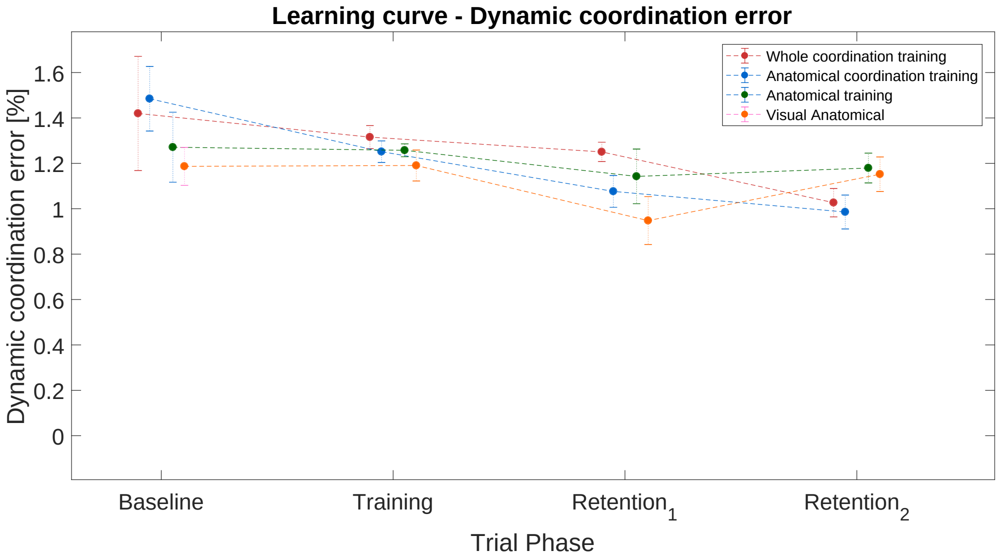


Figure 3.7: Evolution of the subject's error in dynamic coordination metric across trials. Bar graphs are used to provide the standard deviation. Mean performance (i.e. position error) is computed for the 3 baseline, early and late retention trials, as well as for the last 3 trials of the training phase.

In fig. 3.8, the improvement across three time-stamps along the experiment's trials is shown . The error improvement (i.e. decrease) has been computed as exactly as commented in the other metrics.

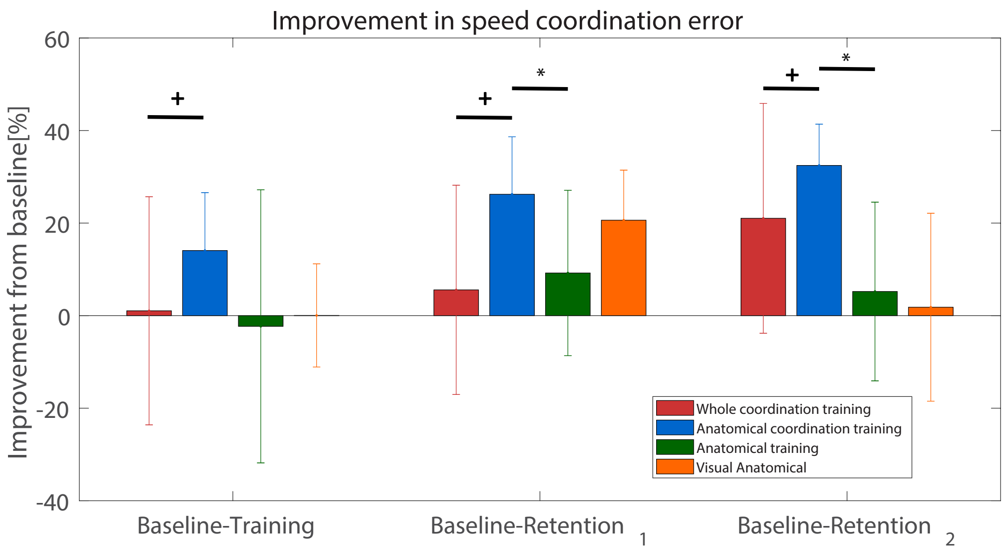


Figure 3.8: Relative improvement (w.r.t baseline performance) of each group in regard of dynamic coordination metric. Comparative hypothesis testing among study design factors for dynamic coordination learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. $p<0.05$ marked with *. $p=0.1$ is signalized with +.

Due to similar situation as before, the non-normal and non-homogeneous distribution of our dataset (more details in

Group 2, or the subjects who were delivered a anatomical-based haptic training with haptic recomposition, outperformed others. However haptic feedback could not show significant contributions to excellence further than in the form of variable superiority. As can be seen (fig. A.12a), the full-arm training resulted, in average, not so effective for the subjects immediately after the training and in the end of the first session ($Mdn_1 = -3.91\%$) against anatomical-specific training ($Mdn_2 = 15.7\%$) [U=4.00,z=-1.155, r= 0.41 medium effect;p=0.12] . Also a trend of inferiority was found between group 1, $Mdn_1 = 13.74\%$ and group 2, $Mdn_2 = 33.82\%$ [U=4.00,z=-1.155, r= 0.41 medium effect;p=0.12] . Benefits of haptic decomposition after a broken down motion reveal as a significant difference in terms of dynamic coordination on a long run($Mdn_2 = 33.82\%; Mdn_3 = 2.05\%$)[U=2.00,z=-1.732, r= 0.61 large effect;p=0.04].

3.1.3. Evaluation of consolidation of a learned skill

The results brought by the investigation of the consolidation phenomenon in our study, are presented in this section. Firstly, it is important saying that the statistical power of the coming results is limited and must be interpreted as a small effect with a significance limited and related to the sample size. Also, I would like to note that, since some of the assumptions in which parametric tests are based (e.g. homogeneity of the variance, normality of the data), were violated. For that reason, again, non-parametric testing was conducted (i.e. Kruskal-Wallis 1-way ANOVA and Jonckheere-Terpstra test). This tests failed to find a significant difference among groups for both time-stamps (between end of training and retention 1 and similarly with respect to retention 2 from training), except for the case of position coordination metric which showed a significantly different performance between groups. A Mann-Whitney U test was used for post-hoc analysis, as will be reported in the following.

To commence with analyzing this set of results, let us report the observations done around the quality of motion (fig. A.13). In these two metrics (i.e. position and speed error), no significant differences between the improvements of different groups were found (Table fig. A.17, Kruskal-Wallis with p>0.1). However, some effects of consolidation can be appreciated in the learning of position. While all groups improved between training and the first retention testing (15-10 min later), between a 2 and 5%, it was group two the one which improved the most($Mdn_2 = 5\%$). This is equivalent of approximately 1.75 degree, which is not such a big improvement, though. This is more apparent though in the long term retention (right side of fig. A.13a), in which it can see that the improvement was higher, around a 10% (equivalent to ≈ 3.5 degrees, see fig. A.5) and benefits of haptic demonstration of the whole motion are apparent (i.e. groups 1 and 2, increased the performance after training, while groups 3 and 4 increased their errors).

Very similarly, in the speed correctness metric (fig. A.13b), the group two (i.e. haptic anatomical training and haptic coordination training) outperformed others, by a 10% (≈ 5 deg/s, see fig. A.6). However, in the long-run, the learning effects diminished, and no memory of speed profile could, apparently, be built. Still the wash-out amount differs between groups, being the haptic coordination training groups (groups 1 and 2) more efficient at the time of remembering a speed profile.

When learning a coordination pattern, some significant differences between groups were detected. In the case of coordination of position (fig. 3.9), a significant difference was found among groups in the KW test (Tablefig. A.17). Therefore, as can be seen analyzing the bar plots (see fig. 3.9) , a Mann-Whitney U test resulted significant between group 2 (i.e. coordination haptic training) and group 3 (i.e. lacking coordination haptic training) [$Mdn_2 = 2.7\%, Mdn_3 = -5.3\%$;U=0,z=-2.309,r=0.817 large effect,p=0.01]. This shows the effect of training a motion all together in a haptic fashion, which is an increase of a 3% in coordination goodness, while a lack of coordination training (i.e. training the motion only separated in components), has a wash-out of almost 8 percentual points. Without being significantly different to the other groups; group 2 also proved to be better than the rest in short-term consolidation, with an improvement over end of training of around 7%. In terms of dynamic coordination, the effects were not significant comparatively among groups (Tablefig. A.17) and also not mention worthy in magnitude (i.e. below a 1% of improvement or worsening, depending on the group and time scope; as can be seen in fig. A.14b).

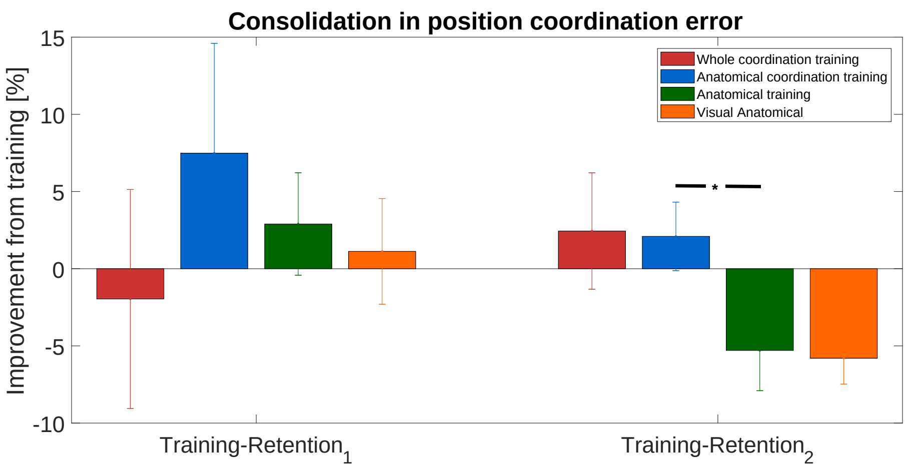


Figure 3.9: Improvement w.r.t. end of training performance in position coordination as a percentage over end of training skill level. p<0.05 marked with *. p=0.1 is signalized with +.

3.1.4. Evaluation of transfer motion's quality of movement

When evaluating the transfer motion (i.e. rugby frontal drilled pass), no statistically significant differences could be reported, i.e. Kruskal-Wallis 1-way ANOVA with $p>0.1$ (TableA.18). This was mainly due to the variance presented in the kinematic features of the performance of the subjects. In figs. A.15a, A.15b, A.16a and A.16b one can see the differences between groups. In fig. A.15a, the reader can see that for learning the second task (i.e. transfer motion), the whole training group (group 1), performed, in average, better than the anatomical training group(group 2). Also, the group which had the trajectory taught separately and later recomposed (group 2), performed slightly better (but did not survive statistical superiority test) than the users which only received training on the sub-components of the motion (group 3). Paradoxically, for position learning, unlike in the case of the main motion to be learnt, the visual group (group 4) outperformed the rest of groups.

This happened unlike for the case of speed learning. In this parameter, the anatomical decomposition of the motion (groups 2 and 3) seemed to outperform the whole motion teaching group (group 1) (see fig. A.15b). However in the long term, the recomposition of the motion seems to be beneficial, as suggested by the superiority of groups 1 and 2 against group 3.

In terms of coordination, the results are varied. Group 1, i.e. whole motion teaching, outperformed other users. In deed, users seemed to get worse in performance with time (see fig. A.16a and fig. A.16b). More effects are quite vague and disperse, therefore more conclusions cannot be extracted from the data. Interesting enough, there seems to be a trend in the position coordination metric(fig. A.16a), suggesting that increasing levels of guidance (i.e. group 1, fully haptically guided, to group 4, fully visually guided), are beneficial for motion coordination learning. Haptic guidance shows a superior retention too (although not significant). This can be seen in the long term retention side of the graph. In this data, it can be seen than the worsening trend of the groups 2 and 3 diminished, while the group 1 got better and the group 4, visually guided, got worse. In speed coordination, no observations can be pointed out.

3.2. User experience

In general, no significant differences were detected between groups in each time-stamp (i.e. end of session 1 or end of session 2, see Table A.19), however some effects can be seen.

For the metric on "Interest and enjoyment" the levels on both sessions were relatively high, implying that subjects enjoyed the task, but no significant differences were appreciated(Table A.19) among groups, being still the groups 1 and 2 (i.e. haptic coordination training with both haptic anatomical or whole pre-training) a bit more "enthusiastic" about the training in the second day (approximately one point above groups 3 and 4).

In the case of subject's "Perceived competence", no significant effects of the group of assignment (see Table A.19), but some trends were detected (Table A.20) after session 1. Jonckheere's test revealed a marginally significant trend in the data: as more guidance was given (i.e. group 1, fully haptic to group 4, fully visual), the median perceived competence increased ($Mdn_1 = 2.83$,$Mdn_2 = 3.5$, $Mdn_3 = 3.6$, $Mdn_4 = 4.1$), J = 68, z = 1.879>1.65, r = 0.47. As can be seen the effect size was not of great magnitude (r=0.47), however this trend is similar to the one obtained after session 2. Jonckheere's test revealed a marginally significant trend in the data: as more guidance was given (i.e. group 1, fully haptic to group 4, fully visual), the median perceived competence increased ($Mdn_1 = 2.83$,$Mdn_2 = 3.5$, $Mdn_3 = 3.6$, $Mdn_4 = 4.1$), J = 65.5, z = 1.652, r = 0.413. This time being the effect smaller than for the previous case.

The "Effort/importance" metric showed certain effects (a trend) of the group assignment on the effort employed for the task($H_{s1}(3) = 5.374$, $p = 0.146$; $H_{s2}(3) = 4.734$; $p = 0.192$) (TableA.19). This is due, mainly, to the significant effect produced by anatomically decomposed guidance on the whole movement (group 2) versus a whole-task guidance (group 1) (U=2.5,r=0.57,p=0.052). Also, the complement of a whole demonstration of the movement (i.e. group 2) seems to marginally increase (in session 2) the effort employed in the exercise, when compared to the absence of this whole practice (group 3); U=4, r = 0.3, p = 0.12. From the data shown in fig. 3.10, one could say that the group which was trained first anatomically and then on the whole task with help of a robot, committed more to the task, although with a limited statistical significant effect. Post-hoc statistics are contained in Table A.21.

Finally, the levels of stress induced by the task, reflected by the metric "Tension/Pressure", were similarly low for all groups (Kruskal Wallis $H(3) \approx 3$ with p>0.1, see Table A.19).

Looking at the long-term effect on motivation when the subjects visited again the investigation site, fig. 3.10) can be used. The changes in the different Intrinsic motivation parameters, after 1 week, can be seen. This reflects the increase or decrease on different motivation factors as a consequence of retained practice skills. In order to observe significant differences due to the group assigned to each subject, I performed a Kruskal-Wallis 1-way ANOVA test. A non-parametric test was selected for violation of the assumptions for conducting a parametric test. The results of the Kruskal-Wallis test are shown in the Table A.19.

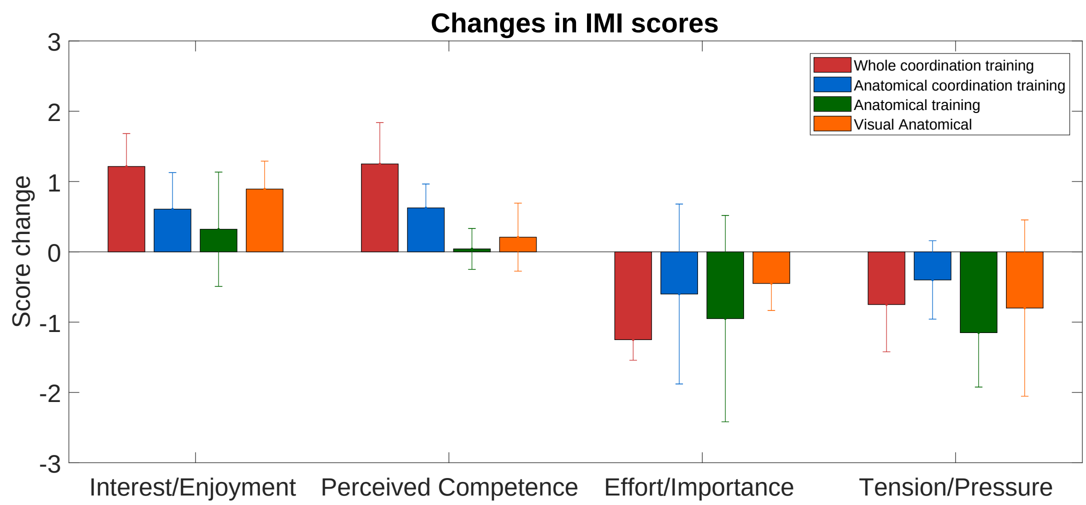


Figure 3.10: Changes in IMI scores. Bars represent the mean score change per subset between session 1 and session 2 for each group. Error-bars represent the corresponding standard deviation for each group. Positive values indicate and increase, and vice versa.

In general, no significant differences could be appreciated (Mann-Whitney U test: U(3)=1-5.5; p >0.1).

However, despite the low sample and the high variance detected in the metric, and after visual inspection of the data, a testing for trends was performed (i.e. Jonckheere-Terpstra). This test gave more insight on the presence of trends (e.g. Perceived competence: J=48, z=2.300>1.65, r=0.575, p=0.021). Due to this fact, and that the p value of the K-W test was nearing the boundaries of significance, I decided to perform some post-hoc test (properly corrected by Bonferonni, when necessary) in order to detect finer differences between groups.

As for the first metric (i.e. "Interest/Enjoyment"), the only test performed (Mann-Whitney U-test) was for testing the hypothesis 2 (i.e. recomposition of the motion is beneficial) which was confirmed ($Mdn_2 = 0.72, Mdn_3 = 0.29$, U=2,z=-1.821,r=0.66,p=0.035, Table A.24b). Although, only this difference was significant, the superiority of whole training (group 1) versus anatomical training (group 2) is apparent in fig. 3.10. Also, visual protocol appears to be improve more than, at least, group 3 (i.e. haptic anatomical training and visual recomposition).

In the domain of "Perceived competence" the level of guidance influenced the existence of a trend (as shown before). The less guidance, the smaller the perceived competence (J=48, z=2.300>1.65, r=0.575, p=0.021, Table A.23). However the only significant difference happened only between the groups being taught in anatomical separated joints when one group was haptically guided for the whole task while the other was only visually guided ($Mdn_1 = 0.5, Mdn_2 = -0.29$, U=2,z=-1.888,r=0.66,p=0.03, Table A.24b). Non-significant difference occurred between group 1 and 2, making slightly better the whole task training in comparison with the anatomically separated training.

As for the last two metrics, i.e. "Effort/Importance" and "Tension/Pressure" respectively, no significant differences were found. A general pattern can be seen, pointing out that subjects being guided in the whole task (group 1) committed with more effort($Mdn_1 = -1.13, Mdn_2 = -0.38$,U=4,z=-1.169,r=0.41,$p \approx 0.12$) and went under more pressure in the training, than subjects guided in the joints separately. Same effect was found in the subjects which being trained anatomically, were taught the whole task only visually (group 3), in contrast to the subjects who were helped to learn the overall task (group 2)($Mdn_2 = -0.3, Mdn_3 = -1.7$,U=4,z=-1.155,r=0.4,$p \approx 0.12$). No statements can be done for the third hypothesis (i.e. "the visuo-haptic training is better than only visual training"). However, also higher commitment and tension was reported by the haptically guided group.

4

Discussion

In this chapter a recapitulation of the results is provided, centering the explanation around the contrasting of the three hypothesis which occupied us in this work. First of all, I would like to analyze whether the postulates of [42] regarding the "part-whole transfer" paradigm held on the study conducted. Secondly, a revision of the superiority of a haptic versus visual feedback streams is analyzed for this novel complex task. Finally, the main innovation of the work, i.e. testing the need of recomposing a motion which has been taught in the components, is commented through.

The last part of this discussion chapter will relate to the pros and cons of using each of the approaches which served to design our experimental groups. Also, some thought on possible combination of each strategies are discussed, too.

4.1. Anatomical or whole motion training?

One of the goals of this study was to reproduce and validate the results obtained by Klein and colleagues [42] which confirmed the "part-whole transfer" paradigm. In that study, the author and his colleagues used a very similar setup to which was used here and a similar task in order to investigate whether simplifying a task by breaking it down to some different sub-components would help motor learning. The result was that the group that got the motion taught in the components which would match with the anatomical joints, learned the motion achieving a more accurate trajectory replication (i.e. lower position error). The control group (i.e. *Whole Coordination Training* group) were subjects who only learnt the trajectory as a whole during the whole practice protocol.

In fact, our study replicates theirs, as can be seen from group 1 (Whole coordination training) and group 2 (Anatomical coordination training). Both of these groups received visuo-haptic guidance in either the whole task (group 1) or the components of this one and then the whole task(group 2). In the first part of Table 4.1, the motion quality parameters are presented comparatively for groups 1 and 2. As can be seen, the group receiving anatomical training in the joint space outperformed the group training the whole motion permanently by a 16% additional improvement after training, confirming hypothesis 1 in what regard to position tracking. This also confirms the results of [42], supporting the "part-whole transfer" paradigm.

Apart from confirming Klein's results [42], the task's performance metrics, as exposed before, were broadly evaluated. In terms of speed profile learning, the number of times that subjects experienced the whole trajectory seems to matter. This difference of a 5% improvement less between groups is not significant (see Table 4.1) but cannot confirm the hypothesis that simplifying the training would increase the learning of a speed profile. In deed, not directly but partially, matches to the existing literature in the sense that haptic guidance enhances speed profile learning in the non-discrete tasks, or time critical task as in [52]. In [52], it was found that certain parameters of speed profile correctness (e.g. "error related to the maximum velocity, the location of the speed maximum, and overall mean absolute error from baseline to retention"[52]), improved with haptic guidance. Especially retention was improved when using haptic guidance, and as stated in [52], especially on less skilled subjects (as our naive subjects were). In this regard, given that group 1 received more haptic guidance of the whole motion, one could expect that it is fair that this group performed better in the speed profile matching, being this a time-critical task. However, it is important not forgetting the lack of power of this contrast, since no significant difference were found, other than a different mean improvement of 5%. So, it seems that simplification and separation of the speed profile of different joint does not help learning, even if the whole trajectory is demonstrated afterwards (as in group 2). Otherwise, more practice of the full task seemed to be beneficial. Nevertheless, the reader must be careful extrapolating this statement to practice, since several factors could account for this (from experimental setup to minimal sample size).

In terms of coordination, both position coordination and dynamic coordination were superior for the users of group 2 (Anatomical coordination training). This is somewhat logical, since the subjects assigned to this group could focus first in the aspects relating each of the joints (understanding to which extent each joint would move) and then understand the time series of the joint angle's combinations necessary to achieve an accurate rugby pass. In the contrary, subjects receiving only the information of the five joints in the form of guided motion (group 1), might have not been able to separate this complex information (in robotic terms, a five terms vector per time stamp). This might explain a superiority of 15% in the improvement of their skills in this regard after receiving training. This can have been also a possible explanation for the results gathered in the study of Klein and colleagues [42]. Also, although with a small effect on speed (or dynamic) coordination improvement, a 17% (which corresponds to a change in error from 1.5% to 1.2%, i.e. 0.3%, see fig. A.8), the difference, between the group training in the whole task domain versus the group training in a more simplified and focused on the joints versions fashion, was marginally significant in favor of group 2 with a 16% more improvement. This was sustained in the long rung (until long-term retention trials, see fig. A.8).

So, after training, group 2 was better than group 1 in all quality of motion parameters with the exception of speed; suggesting that anatomical simplification of the motion made the task easier for the subjects to learn. This translated to motion correctness terms. Speed profile learning might still require only practice of more complete motions, or a different phase of learning dedicated to that aspect.

In the long run, the anatomically trained group (group 2), also showed better coordination patterns, this time significantly better than the group 1, for the position coordination metric (20% better, which translated in a 10% lesser error in position coordination, against a 5% lesser coordination error of group 1). A non-significant difference between groups is also existing for the case of dynamic coordination, where the anatomically trained group improved 13% more than the group training with the whole task permanently. No remarkable consolidation effects were detected for the group 1, for any of the parameters, meaning that there was no off-line learning for their subjects, so most of the learning occurred during the training for these subjects. Group 2 obtained off-line gains in the position error reduction and marginal improvements in coordination (only position coordination) and the speed profile learning, not significantly different from the achievements of users in group 1, though. It seems that the fact of separating the teaching of each joint's motion (group 2) has positive effects on learning position tracking and coordination aspects, but not speed profile. This also applies for the retention of this knowledge along time, with special mention for the coordination aspects of the practice. Might it be the case that, brain encodes in a better way coordination patterns when their components are clearly represented in the brain (as was the case of group 2). As suggested in the metaphor of Bizzi [5], internalizing an "alphabet of motions" might make easier its practice and recall (i.e. retention).

Does this apply, conversely, to performance in other task?. Is it possible to transfer the skills learned to another task? Only in the case of speed coordination, the breakage of a motion down to its components resulted substantially more beneficial (see Table 4.1). In fact, the results of transfer movement (Frontal rugby drilled pass) are contradictory to the ones obtained from the practice with the target movement (lateral rugby drilled pass). Even more, the results for trajectory tracking showed a reduced learning for the anatomically split motion in comparison with the whole motion demonstration. This might be due to the fact that both motions resulted to be too different, that the frontal pass involved an inverse coordination pattern, or the fact that the robot induced too much disturbance onto the subjects who eventually did not manage to compensate in order to achieve in the task. In any case, both groups transfer the knowledge, improving their performances in all four motion features up to a 25% (position correctness, whole anatomical; see Table 4.1. This shows, opposite to what was found in [42], that transfer of motion is possible, and that no major differences on how this is achieved could be found. This implies that transfer of motions can be dependent, not in the performance on a certain task, but on the type of motion and its relation to the base motion learned. This reinforces the idea that there might be families of motions which are similar and therefore more "transferable" [5, 68]. However, when looking at our results one cannot conclude that any of the strategies followed could dominate at transferring knowledge to the alternative motion. For now, it can be stated that teaching the whole motion, all the time was more effective. Let us come later over the results of the other groups in order to make more hypothesis on the topic.

Finally, in terms of motivation, self-feeling and effort, the IMI showed us that the group that was more guided "felt" more competent and interested after the training, in the retention, than the group that got guided in separated joints. Also, the levels of effort and pressure while conducting the task, dropped more after training with full haptic guidance, and not so much when the guidance was specific for the joints. This, in fact, shows a logical effect. The subjects feel more comfortable (less pressed) and more competent, with the subsequent effect of more enjoyment; when the task is assisted. However, this has a negative repercussion on performance, phenomenon known as "guidance hypothesis" [82]. The author says there that "practice in conditions with relatively infrequent exposures to augmented feedback was as good or better for learning than practice in conditions with relatively frequent exposures to augmented feedback". The fact that the whole motion was not so frequently practiced by group 2 as by group 1, allowed less supervision of the subjects, which might have elicited more exploratory attitudes on the subjects, for example by provoking subjects to reflect on how the joint's singular motion profile interplay with other joint's pattern in order to make a more complex movement. This second fact has also been reported to be crucial for motor learning[69]. Indeed, the same results obtained by Duarte and colleagues back in 2015[19], can be seen in Table4.1. Higher levels of self-efficacy and enjoyment with increasing levels of guidance on a certain task. In both cases, the human factor and the motivation of the user have probably elicited.

Note that all results are statistically valid only to the extent of this study, its small sample and the limitations of our experimental setup. However, the results can stand for a defense of the "part-whole transfer" paradigm. In line with its postulates, the main motion was learned more efficiently both in trajectory tracking and coordination aspects by the group who got it simplified (group 2). Retention was also better for them, probably as a result of getting each feature of the task in a more separate fashion, easier to identify and neural encode. Transfer occurred for both groups similarly for all possible kinematic parameters. However, the human user seems to get a better time when being more guided, although this impacts negatively his or her performance. This is somewhat logical, since users can relax more and trust the robot, but when the time is come to show the acquired skills, not so many strategies were developed and not so much effort was put in learning and the performance is affected. So, confirmed "guidance hypothesis" and the results of Klein and colleagues [42], another aspect which is of outmost importance in motor learning is here addressed: the visual or visuo-haptic system's suitability for teaching of a complex task.

Parameter	Whole coordination	Anatomical coordination	Hypothesis testing	Difference	Sgn.
Motion Quality	9.25%	19.75%	✓	10.50%	
Position	15%	31%	✓	16%	
Speed	15%	10%	✗	-5%	
Coordination	6%	21%	✓	15%	
Dynamic C.	1%	17%	✓	16%	+
Retention	21.81%	30.92%	!	9.11%	
Position	35%	44%	!	9%	
Speed	11%	13%	!	2%	
Coordination	28%	47%	✓	19%	*
Dynamic C.	21%	34%	✓	13%	
Transfer	10.81%	13.05%	!	2.25%	
Position	25%	11%	✗	-14%	
Speed	7%	11%	!	4%	
Coordination	13%	15%	!	2%	
Dynamic C.	6%	16%	✓	10%	+
Consolidation	0.50%	3.25%	!	2.75%	
Position	2%	8%	!	6%	
Speed	-4%	2%	!	6%	
Coordination	4%	3%	✗	-1%	
Dynamic C.	0%	0%	!	0%	
UserX experience					
Interest	1.21	0.6	✗	-0.61	
Competence	0.82	0.5	✗	-0.32	
Effort	-1.13	-0.62	✗	0.51	
Pressure	-0.75	-0.4	✗	0.35	

Figure 4.1: Recapitulation table for testing hypothesis 1. For all parameters the positive values relate to percentual improvement of a certain feature, except for the User experience (UserX) where positive values imply increase and negative values a reduction of the specific marker. The column hypothesis testing marks differences bigger than 10% with a "check" mark, which would support superiority of Anatomical coordination, while negative values imply the opposite. The column hypothesis testing marks differences bigger than 10% with a "check" mark, which would support superiority of Anatomical coordination, while negative values imply the opposite (marked with and "X"). For the UserX parameters and increase in Interest or Competence of bigger magnitude than 0.2 differential points was signalized with a positive mark, while scores which did not differ so much are marked as negative hypothesis testing (i.e. "X"). Inverse interpretation is used for the "Effort" and "Pressure" items, where a bigger decrease on the score would be recognized as a positive hypothesis testing, and vice versa. The summary headings with gray background intend to show the mean overall score (of all features) for a certain time frame comparison: after training, in long-term retention, for the transfer motion or between end of training and long-term retention/consolidation). User experience items score alone. Significance supporting hypothesis 1 with $p<0.05$ marked with * and $p=0.1$ is signalized with +.

4.2. Visual or haptic training?

Another well documented aspect in the motor learning field is the effects of using either visual or visuo-haptic feedback in the training of complex skills. This has proved to show different effects, for different parameters of motion. For example, already in 2002, Feygin et al.[22] stated the better suitability of haptic or visuo-haptic feedback for the learning of a speed profile, or any dynamic transformation, while shape and position learning was improved more by means of using visual feedback alone. Similarly, a similar improvement between baseline and end of the training, was found, in both visuo-haptic group (group 3) and visual training group. Both of them were visually trained in the recall or demonstration phase of each practice block, however the intervention differed on the removal of haptic guidance. The errors in the angular position (i.e. trajectory tracking) incurred in by the subjects of group 4, visual feedback only, decreased after training more than for the group receiving haptic guidance. This was a small difference though (see Table4.2. Nevertheless, this would not be surprising; since already Feygin found out that visual feedback alone doesn't happen to be detrimental for motor learning. In deed, both groups compared here performed similarly when judged upon performance in the shape correctness (position error). This confirms then the hypothesis stated in literature that visual and visuo-haptic feedback are equally efficient for motor learning.

In terms of speed profile learning, the visuo-haptic training group improved more (around a 6%) than the visual only group, which is an already reported finding which occupied the works of several authors (see [22, 52, 74]. In terms of coordination, similar effects were detected, improving the coordination more when a haptic training is applied, even if no whole motion is taught, which gives an idea that visual feedback can give some hints in both the coordination of the joints and the speed profile learning of a full trajectory, even if no haptic provision is used for that purpose. This phenomenon was already detected by Feygin[22] ("having vision during the recall significantly improved performance, thus indicating that timing information can be distilled from visual perception"). Later we will see if it is enough or whether complementary information is provided by haptic re-composition, improving motor learning.

Another interesting effect stated in the literature and confirmed here is the fact that retention is better in the case of visuo-haptic training, comparatively to only visual training, with a significant effect in the coordination learning (see Table4.2). This is also expected, after having read the work of Duarte et al. [19], who also found that effects of haptic guidance prevail more in time and also induce more motivation, improving the changes of still increasing the performance. This can be seen both in position, and in the coordination improvements in the long term, especially in the position metric. This is contradictory to the results of [74], which did not find a big effect on the addition of haptic feedback to the visual feedback group. However, the tasks were intrinsically very different (rhythmic rowing task versus a discrete ballistic motion of rugby).

Interesting enough, the visual group did not only stop improving, but also worsen its performance in terms of speed profile performance and coordination in the latest session. This can be due to the disturbing nature of the robot onto the subjects, which might have made the subjects learn a wrong speed and coordination profile which mismatched the visual information they were getting, together with the forgetting that happened along the days between visits to the experimental facilities. For understanding this results, one should think of the robot in transparent mode as an error augmentation case, in which the user has to fight a force field. However, since there is no model controlling this disturbance, unlike in the work of Marchal and colleagues [52], like a flux field, or in [74]; it is possible that the subjects did not get a useful error augmentation, which would trigger learning, as expected from the mentioned literature.

Transfer was affected by the mix of feedback modalities, as can be extracted from the poor improvements of group 3 when compared with the visual only group. The interferences between haptic knowledge with visual information apprehended, might have been the cause of this. Probably, the information was not properly consolidated and harmonized (between proprioceptive and visual streams) when integrating the subcomponents of the motion, and then it resulted complicated to figure out how to coordinate the motion to compose a meaningful forward pass. Also, in this kind of movement, the overall coordination was of big importance, and might have been the case that group 3 (visuo-haptic training and visual re-composition), had some trouble to deal with the robot in transparent mode, while the visual-only group had more experience dealing with such a disturbance, therefore having explored more strategies in order to counteract the big robot-related inertia they had to move in order to perform. This data, of transfer motion performance, shows that a remarkable learning of a novel motion can be also trained only visually to an acceptable level of excellence. Indeed, the improvements of the visual group in terms of all kinematic, for the transfer motion, were higher than for the target motion and considerably bigger, too, than the corresponding improvements of other groups for this forward pass (transfer motion in retention 2, see fig. A.15). This could be due to the fact that group 4 "knew better the robot", or because of motivation factors, as it will be seen in the IMI results.

In terms of consolidation, nothing can be stated, other than subjects assigned to both groups showed, none off-learning, but rather forgetting of the task learnt. This can be seen in Table4.2 and fig. 3.1,fig. 3.3,fig. 3.5 and fig. 3.7. The same forgetting rates were registered in both groups, which contrast with the off-line learning presented by groups 1 and 2, haptically training in the overall coordination pattern, as can be seen from comparison of Table4.1 and Table4.2. This suggests that haptic recomposition might have helped in building solid grounds for motion practice, in terms of coordination and other kinematic parameters.

Lastly, the provision or absence of haptic guidance showed also several effects on self-reported factors, such as interest, reported competence, or reduction of pressure during practice. In first place, the more the subjects practiced under the robotic disturbance (i.e. the robot in transparent mode), the more challenged they "felt" as can be seen in the higher interest and self-competence reported. Also, even if both groups felt as alerted or pressured under the training (see last part of Table4.2), the group of visual guidance only had a plus of reportedly felt challenge, which together with the motivating factors (i.e. interest and self-competence) induced in them a sense of competition, which positively affected the task performance, as can be seen in the performance on the transfer motion or in position tracking improvements (Table 4.2). Conversely, the guidance provided to group 3, who felt in the joints the haptic assistance, reduced the stress on them and probably the effort put on the task, as ascertained by IMI results. This is compatible with the "point-challenge theory" [30]. This could apply to our case in the sense that the "challenged" only-visual users (group 4), had more experience in using the robot, which together with their increased interest in learning (from IMI results), made the functional difficulty of the transfer task more attainable than for other groups, including group 3. Contrary to this, the haptically guided groups, were not used to this task, and probably felt overwhelmed about performing on it. That could explain lesser improvement of groups 1 and 2 when comparing them to group 3 (see fig. A.15). However, this reasoning does not explain the good performance of group 1, as well in transfer motion, unless explaining the situation being due to different subjective predisposition of the different groups to face the new challenge of the transfer motion. For this reason, more data analysis should be conducted.

In the following, the results related to the clarification of our second hypothesis, about the need of recomposing a broken down motion, will be presented.

Parameter	Anatomical haptic	Anatomical visual	Hypothesis testing	Difference	Sgn.
Motion Quality	9.50%	7.75%	!	1.75%	
Position	17%	18%	✗	-1%	
Speed	12%	6%	!	6%	
Coordination	12%	5%	!	7%	
Dynamic C.	-3%	2%	✗	-5%	
Retention	6.82%	-11.00%	✓	17.82%	
Position	24%	6%	✓	18%	
Speed	3%	-25%	✓	28%	
Coordination	6%	-20%	✓	26%	*
Dynamic C.	5%	-5%	✓	10%	
Transfer	2.62%	14.25%	✗	-11.63%	
Position	-3%	24%	✗	-27%	
Speed	0%	11%	✗	-11%	
Coordination	6%	12%	✗	-6%	
Dynamic C.	7%	10%	✗	-3%	
Consolidation	-4.50%	-5.00%	!	0.50%	
Position	-3%	-3%	!	0%	
Speed	-10%	-11%	!	1%	
Coordination	-5%	-6%	!	1%	
Dynamic C.	0%	0%	!	0%	
UserX experience					
Interest	0.32	0.9	✗	-0.58	
Competence	-0.29	0.2	!	-0.49	
Effort	-0.62	-0.62	!	0	
Pressure	-1.15	-0.8	✓	-0.35	

Figure 4.2: Recapitulation table for testing hypothesis 3. For all parameters the positive values relate to percentual improvement of a certain feature, except for the User experience (UserX) where positive values imply increase and negative values a reduction of the specific marker. The column hypothesis testing marks differences bigger than 10% with a "check" mark, which would support superiority of Anatomical haptic, while negative values imply the opposite (marked with and "X"). For the UserX parameters and increase in Interest or Competence of bigger magnitude than 0.2 differential points was signalized with a positive mark, while scores which did not differ so much are marked as negative hypothesis testing (i.e. "X"). Inverse interpretation is used for the "Effort" and "Pressure" items, where a bigger decrease on the score would be recognized as a positive hypothesis testing, and vice versa. The summary headings with gray background intend to show the mean overall score (of all features) for a certain time frame comparison: after training, in long-term retention, for the transfer motion or between end of training and long-term retention/consolidation). User experience items score alone. Significance supporting hypothesis 3 with $p<0.05$ marked with * and $p=0.1$ is signalized with +.

4.3. Haptic or visual recomposition?

In this section, groups 2 and 3, which practice differed only on the addition of a haptic demonstration of the whole motion (group 2), are compared. The comparison of their performance gives us interesting and valuable information our interest to understand the importance of the haptic information in order to learn the full motion.

As far as the position tracking performance, or the goodness of the trajectory made by the user, the need of full motion recomposition is apparent. Indeed, the group who was provided with full motion haptic teaching improved around a 14% more than the group who was only shown the full motion visually. The improvement of group 2, i.e. haptically recomposed motion, was of a 31% after training (approximately, 10 degrees less error than the baseline level (see fig. 3.1). This would make sense, since haptic guidance has proven to be effective in providing proprioceptive information on the Range of Motion (RoM) of a movement. Additionally, when provided in combination with visual feedback, as it was the case, the effect is a better performance in motion replication. In literature, there are several cases of success on what relates to haptic guidance for teaching complex motions [19, 22, 52, 74].

Indeed, the latter, a work of Feygin[22], showed a possible explanation for the bad performance of removing the haptic guidance on training of the whole motion. This could be assimilated as the recall condition of Feygin's experimental setup. In the study, the different combinations of training (haptic, visual and visuohaptic) were studied in interaction with different recall conditions. The results was that different combinations of training and recall conditions would give distinct levels of performance as a result. It was found that visuohaptic training and recall had been the most successful practice combination, similarly to what can be seen in group 2, visuohaptic training and visuohaptic recomposition. This combination seems to present a proper compatibility and might help in integrating both information streams in an optimal way for motor learning. Feygin et al.[22] also found an interfering effect between haptic and visual feedback in badly designed setups, as already stated by Adams in the past[2]. Adams stated that the different modes used in skill acquisition training and recall training (our re-composition repetition), can produce interferences in the learned skill. Might be due to errors introduced in the sensory-motor model of the task (which was proposed by Wolpert et al.[45], but the fact is that the different modality of practice spoiled for group 3 (haptic training and visual recall) in what relates position learning and that might have been responsible for a lesser improvement of this group.

In what relates to speed learning, both groups improved as much, around a 10% reduction of errors w.r.t. baseline. There were not significant differences in the amount learnt. This is also in agreement with literature which states that speed profile learning is benefited by haptic guidance[22, 52]. However, it does not explain why the lack of haptic feedback had no repercussion (i.e. similar level of improvement achieved).

Instead, in the long run stronger effects can be appreciated. It is apparent that haptic guidance of the whole motion affected positively in the form of error reduction in position tracking (44% of improvement, i.e. 20 degrees less errors than in the baseline), and better coordination patterns (a reduction of a 47% in coordination metric). Also, better dynamic coordination (34% more than for group3) was exhibited. All this comparisons between groups (position and coordination) resulted significantly bigger in favor of the group 2 ($p<0.05$). This points out the better retention of skills possible by first simplifying a task (by reducing the training to the separate joints) and later re-composing the motion. This build up process seems to be beneficial also for speed learning. Group 2 learned a 10% more than group 3, still one week after the training. The overall improvement, after retention 2, was of 13% (equivalent to around 10 deg/s, see fig. 3.3). This shows that still after learning, subjects improved around 3% more. This off-line learning was 12% bigger than for group 3, which indeed had a forgetting of the speed profile memory of around 10% (Table4.3).

Group 2 exhibited off-line learning, also known as consolidation for several aspects. Position off-line learning was also 11% significantly better after training (an improvement of 8% in position error, equivalent to 10 degrees, down to a sole error of 25 degrees) than for the group who could not use the haptic recomposition of the whole motion as learning base (group 3). The latter forgot up to a 3% of the skills acquired at the end of the training. Speed kept a learning improvement after training of 2%. However, group 3 could not do anything but forgetting the speed profile, increasing the errors in 10% (i.e. around 5deg/sec more error w.r.t to training level). Coordination parameters kept improving after training at a rate of 3%, while the forgetting rate for group 3 was of 5%. No remarkable changes in dynamic coordination for both of the groups.

It seems from this data that the retention of the skills is very positively affected by breaking down a motion and haptic assistance for its recomposition. It might be the case that sensory facilitation occurs in the case of group 2, when learning speed, position and coordination parameters. This phenomenon has been reported in several studies (as gathered in Sigrist's review [73]. The phenomenon has its roots on the strengthening of connections which host the multimodal representations of task kinematics and dynamics. This effect has been found mainly in cases where congruent feedback is used, as it is our case, and might be due, according to the review[73], to the fact that the information flow is distributed among all possible sensory sources, reducing the cognitive load and the reduction of the interferences which might arise from having to encompass similar or, even worse, contradictory information coming from different sensory streams. The latter could be the case of group 3, were users have to deal with a situation in which haptic channel is used to provide useful information during part of the training (in the joints), and later, the same channel turns out to be a disturbance source (being the robot not perfectly transparent). This might create a neural "confusion" by which the information coming from the haptic flow, potentially improving the performance in variables which normally would do (i.e. position and speed profile learning), might deteriorate them.

As a consequence, also transfer of skills is expected to decay. Indeed, while both position and speed learning, got better for the new alternative motion (front drilled pass), group 3's users developed in a negative trend in the respective motion features. Again, absence of haptic recomposition of the motion might have had a negative impact in the transfer of skills to a similar motion. Similarly, happened in the case of coordination learning, with improvements of 15% for the group 2 users versus a decrease of the errors of only 6% for users only receiving visual teaching of the full motion.

The higher scores in motion performance, had a clear positive repercussion in terms of motivation and competence of the subjects. Subjects scores substantially better (around 0.3 points more in interest and 0.8 points more in self-perceived competence) in the group 2 than in group 3. However, this was not at the cost of more effort, nor undergone pressure while practicing. Indeed, group 3's users saw their stress diminished in around 0.8 points with respect to baseline while practicing. This is a paradox, since the enjoyment was higher for the subjects in group three, thus making us expect also less pressure. The result might be explained by an overwhelming correcting effect from the robot side, experienced when having more guidance, instead of more freedom to learn the full motion.

In short, subjects performed better, with the exception of equal levels of performance in terms of speed profile learning. Also retention was higher under the anatomical coordination training group (group 2), this due to a consolidation phenomenon. Transfer was only possible with the help of the robot during training of the whole motion. Interest and competence feelings were higher with guidance on the whole motion, but subjects went through a more tough and stressful routine. Overall, group 2 seemed more skilled and comfortable with the performance, which translated in positive results when learning the motion (indeed, both of them). Therefore, it is apparent that the haptic demonstration of the full motion is not only beneficial, but also necessary in order to learn a complex motion efficiently (higher learning in same time). Also, the information provided by means of haptic and visual streams, seemed to persist longer in memory and in better conditions, which allowed intersensory facilitation and consolidation (i.e. off-line learning). As suggested in previous literature [73], the distribution of the cognitive information seems to facilitate the learning process to the subjects. This can be used in the future in combination with other techniques.

Indeed, several of the metrics point diverse strengths from the different strategies here evaluated. In the following section a full comparison is done, in order to briefly summarize the pros and cons of each approach, in order to get a clearer view of what kind of tool might have benefit which feature. By correctly selecting and harmonizing different approaches, a more comprehensive training can be generated which helps leveraging pros and cons of different techniques.

Parameter	Anatomical coordination	Anatomical haptic	Hypothesis testing	Difference	Sgn
Motion Quality	19.75%	9.50%	✓	10.25%	
Position	31%	17%	✓	14%	
Speed	10%	12%	✗	-2%	
Coordination	21%	12%	!	9%	
Dynamic C.	17%	-3%	✓	20%	
Retention	30.92%	9.50%	✓	21.42%	
Position	44%	24%	✓	20%	*
Speed	13%	3%	✓	10%	
Coordination	47%	6%	✓	41%	*
Dynamic C.	34%	5%	✓	29%	*
Transfer	13.25%	2.62%	✓	10.63%	
Position	11%	-3%	✓	14%	
Speed	11%	0%	✓	11%	
Coordination	15%	6%	!	9%	
Dynamic C.	16%	7%	!	9%	
Consolidation	3.25%	-4.50%	!	7.75%	
Position	8%	-3%	✓	11%	*
Speed	2%	-10%	✓	12%	
Coordination	3%	-5%	!	8%	
Dynamic C.	0%	0%	!	0%	
UserX experience					
Interest	0.6	0.32	✓	0.28	*
Competence	0.5	-0.29	✓	0.79	*
Effort	-0.62	-0.62	✗	0	
Pressure	-0.4	-1.15	✗	-0.75	

Figure 4.3: Recapitulation table for testing hypothesis 2. For all parameters the positive values relate to percentual improvement of a certain feature, except for the User experience (UserX) where positive values imply increase and negative values a reduction of the specific marker. The column hypothesis testing marks differences bigger than 10% with a "check" mark, which would support superiority of Anatomical coordination, while negative values imply the opposite. The column hypothesis testing marks differences bigger than 10% with a "check" mark, which would support superiority of Anatomical haptic, while negative values imply the opposite (marked with and "X"). For the UserX parameters and increase in Interest or Competence of bigger magnitude than 0.2 differential points was signalized with a positive mark, while scores which did not differ so much are marked as negative hypothesis testing (i.e. "X"). Inverse interpretation is used for the "Effort" and "Pressure" items, where a bigger decrease on the score would be recognized as a positive hypothesis testing, and vice versa. The summary headings with gray background intend to show the mean overall score (of all features) for a certain time frame comparison: after training, in long-term retention, for the transfer motion or between end of training and long-term retention/consolidation). User experience items score alone. Significance supporting hypothesis 2 with $p<0.05$ marked with * and $p=0.1$ is signalized with +.

4.4. What are the benefits of using each strategy?

To conclude the discussion, it would be useful leaving a sense of understanding in a broader sense of the implication of the hypothesis testing which has been done up to now. That is why here it is presented a broad comparative of what each strategy gave to our volunteers to face the challenge of learning a complex motion. For comparing each group, I will go through all our outcome measures and see what were the advantages and disadvantages of applying one or another strategy.

Trajectory shape learning In first place, it is clear (seeing Table 4.4 that the reduction of trajectory shape errors was of higher extent for group 2, which was already the most successful in [42]. The fact of breaking down to the joint the motion in the fast part of the training, brought an advantage of 10% extra learning after training for this group (in comparison to the users which trained the full motion constantly. Similar advantageous effects apply for adding a full haptic motion training in the end of the subcomponent training block (difference between group 2 and 3). The advantages became more clear, when comparing to the subjects which had no haptic training at all. This findings concur to what was already found in literature, confirming the superiority of augmented concurrent feedback in visuo-haptic fashion when this one is well designed. For example, Feygin[22] had already stated that visuo-haptic feedback is superior to visual alone, which at the same time is superior to haptic alone. It cannot be ascertained fully, with the dataset, the second affirmation, other than basing it in the comparison between the anatomical haptic and anatomical visual groups, which show a partial tie in improvements. However the findings of Feygin can be confirmed, in what related to superiority of visuo-haptic with respect to visual alone, in the full motion practice addition between group 3 (anatomical haptic) and group 2 (anatomical coordination training).

Speed profile learning Also, it was found by Feygin[22] and others [52, 74], that the speed profile learning is enhanced by means of either visual or auditory feedback, which can be seen in our study on the superiority across trials of the haptic groups versus the visual group(Table4.4. Indeed, for the speed profile of the full motion, the group which received more haptic training (group 1), succeeded to a bigger extent in this criteria. In this terms, no superiority of anatomical training was found. Rather a statistical tie was found with comparing it to the results of group 1. Whether this results are due to the experimental intervention or other factors (human motivation, robot interaction, etc) cannot be distinguished by using this dataset. However, in terms of motivation certain superiority can be appreciated, of the group 1 with respect to group 2, as well in perceived self-competence and drop of effort employed to accomplish the training. Might it be that the speed profile was learned in a better way by observing the overall trajectory more time or because the benefits of joint-based training impact other aspects of motor learning rather than speed profile learning cannot be understood from this experiment and should be investigated alone in the future with a bigger sample.

Ecological theory of learning What seems clear is the superiority in terms of coordination of the group receiving a haptic coordination training (group 2), against all others. This might have been the principal cause of the superiority in position errors tracking, as well. This is, to me, completely logic, since when agreeing with postulates of Bizzi and colleagues [5], the movement library is build up in a more progressive and, probably, stable manner. Later, recomposition of the full motion is provided to the subjects allowing those to put each note on the pentagram in the most efficient way. This, I had hypothesized would increase motor performance, as it is the case. It is also in line with the postulates of the ecological dynamics of motor learning of Keith[39] , which advocates for a progressing elaboration of motor learning, offering more environmental information to the practitioners with progression of learning and skills acquired, on a basis "offer as much learning as it is possible to apprehend at each time stamp".

Retention of learning The saving in learning acquired during training stayed substantially longer for subjects in group 2, in comparison with other subjects allocated to other groups. One week after, subjects in haptic groups (group 1 to 3) continued learning the shape of the trajectory (see Retention and consolidation results in Table4.4. Also the speed profile was learned better after finishing the training, even one week later, by subjects in haptic groups, which makes sense when compared to already existing literature. The superiority of group 2 against groups 1 and 3, in terms of shape learning, tells us that learned trajectory shapes by means of visuo-haptic concurrent augmented feedback stays longer in memory, and engraved with a more permanent stamp which allows even consolidation effect (i.e. off-line post-training learning). Contrary effects could be appreciated for the non-haptic groups (group 3 and 4), which had distinct levels of forgetting, confirming the volatility of visual memory, in comparison with other memories (such as auditory or haptic, as ascertained in [66, 74]).

Also the speed profile learning was more persistent in groups provided with visuo-haptic teaching of the full motion, with a small advantage of the anatomical group, compared to the full motion practice group. Indeed, after training, all groups but group 2 (see consolidation epigraph on Table 4.4) had forgotten a portion of their speed profile knowledge, while group 2 continued learning one week later.

This effect might come hand in hand with the extended improvement in what relates coordination patter retention. This is where the most significant differences can be found, between groups in our study. This category was broadly dominated by the group who followed the "part-whole transfer" paradigm (i.e. group 2). After being exposed to this training protocol, users in group 2 retained the coordination patter and build it up, reverting on an increase of performance of 47% one week after the training. This happened while other groups did no achieve so substantially (see results on Table4.4).

Transfer of learning learning Transfer of the knowledge to other motion was however dominated by group 4 (visual anatomical training), followed shortly by groups 2 and 1, in this order. It seems, from the dataset, that group 4 "accepted better the challenge" of the new motion, and, no matter why, performed more homogeneously across different criteria. For example, regarding position tracking, the groups which improved the most were the groups 1 and 4, around 25% (see Table 4.4). However, group two did only improve an 11%. This difference in improvement rates can be due to several reasons. One reason can be that subjects in group 2 might have not understood the new task. Another problem might be that coordination patter of the new task (frontal drilled pass) was substantially different from the target task (lateral drilled pass), in what relates to relative timing of axis three with respect to the other ones. It was also, as reported verbally by the users, complicated to articulate this motion inside of the robot, because of mechanical singularities of the system. Therefore we have to be careful when extracting conclusions about transfer.

A potential explanation of this bad result on position tracking of the transfer task might have been that subjects were still recalling the old motor programme and not correctly adapting it to the new case. Therefore, subjects who achieved better in the criteria relating target motion, would have more to "convert" to the transfer motion. That might explain why there is a complementary distribution of the improvements. This is, the subjects assigned to groups which performed noticeably good in the target motion (see position and speed improvement percentages of group 2 and 1, respectively, in Table4.4) would had a poorer improvement in the transfer task; and vice versa. This might indicate that in fact the two motions were substantially different and complex to learn. In fact, what appears reasonable from the data, is that subjects had to "learn to tune" or "unlearn" one pattern to achieve in the other one. However, it is a fact that all of the subjects managed to improve their performance in the transfer task across time, without training on this one. Nevertheless, causality relationship cannot be established, with the intervention made in the experiment. Similar argument can be applied to the coordination metric, were none of the groups improved considerably more than others. Speed profile learning showed similar effects in all of the groups with the exception of group 3. All of them transferred better after retention with improvements ranging between 10% (group 1) and 20% (group 2). No interaction was found with the factor group. Therefore using none of the metrics can we assess whether the learning of the transfer motion was an effect of the training mode provided or just natural learning of the task, as it would be for a new motor task.

User experience In general terms, the group being guided along the whole task(group 1), had a better time(i.e. more interest and perceived competence), than the group being taught in the joints first and then in the overall task (group 2), haptically. However, group 1 had to put more effort on that and experience more pressure under performance, than group 2. The difference between haptically recomposing or not the overall task, after component training (this is, training in the joint space), produces a similar effect of more enjoyment and perceived competence. However, not providing the recomposition instructions of the task (group 3) increases the effort and tension on the subjects. Finally, it seems that anatomical training by only visual means resulted in higher enjoyment and competence, while it also required less effort and produced less stress, in comparison with a haptic training in the anatomical joints.

The data of the questionnaires show that the more the subjects were guided (group 1), the more the perceived competence score raised, which makes sense and has already been reported [19]. Interest was also raised more with more guidance, except for the case of visual feedback, which raised too around 1 point in the Likert scale. The effort employed dropped more too under the more guided group, which was expected. And the pressure dropped the most for all groups except from group 2 and 4 which still went under some tension while practicing. From this, we can understand that guidance reduces effort, increases interest and perceived competence. However, when the guidance is firstly provided in the joints and then re-composed (group 2), the interest and competence drop; maybe because of a bigger cognitive loading. Also, the effort and pressure experience on practice were higher than for a whole guidance. We can understand that this new learning strategy (i.e. building up from joint based learning to full-motion) implied more cognitive demand on the subjects. This has a double implication. On one side, the fact that the perceived competence was lower, helps increasing engagement, in order to get better (as shown by lesser reduction of effort, when compared to group 1). Another advantage is that subjects were driven to put "thinking" in the process, which probably elicits other neural processes. The fact is that this two folded effect did help improving motion quality and retention of this learned skills to a higher extent. However, removing the single demonstration of the whole motion on haptic fashion (group 3), on each block, had very negative effects in terms of retention, consolidation (i.e. there was forgetting) and lesser improvement of motion's quality features. Additionally, the perceive competence decreased after the training and not in a positive way, since it probably triggered frustration feelings (lower interest increase, diminishment of competence feeling, and decreased pressure feeling, see Table4.4).

Importance of recomposing the motion It is interesting to see, that indeed, the re-composition of the broken down motion played a role in Klein's study [42]. It can be seen in the diminished improvement in terms of motion quality, retention, transfer, consolidation and all questionnaire parameters [1], when comparing against the group which got the information about the full motion in a haptic manner. Therefore, it is possible understanding that the haptic information of the full motion helps encoding in a better and more persistent way the skill learned, which also transfers easier to other tasks. This can be related to the results and thoughts of both Feygin's group [22] and Adam's works [2], where it is hypothesized the negative interference of visual and haptic feedback modes. This can speak for the design of systems which provide teaching in a bottom-up learning workflow (where more simple tasks are practiced first, and lately more complex motions are built upon these components)[39], as it was done by Klein and colleagues[42], for example. However, it is important to keep in the loop the learning of the full motion, haptically, as it was hypothesized too by Hogan in [36].

Harmonizing different approaches So, how can all this knowledge be harmonized? A first piece of knowledge gained in this study is the fact that anatomical training in the joint space is beneficial for trajectory shape learning (as ascertained too by the study of Klein et al[42]) and coordination pattern instruction. Therefore, one could think that starting at a lower level of task complexity is a good idea. A second fact learnt from our study is that whole practice is necessary and beneficial, too. Indeed, for some parameters such as speed profile training, the group which trained more the whole motion performed slightly better. Therefore, motion re-composition should be included. It is not possible to infer, though, from our data, the frequency and amount of the whole motion demonstration (since only a single frequency for all groups, i.e. 1 out of 9 repetitions, was used). Also, compromise solutions between only visual and visuo-haptic approaches, such as assist as needed [50], path control[52, 74] or other fading guidance hypothesis[52] could not be investigated, in this work. These approaches might be a good compromise between anatomical and full motion training, and between haptic and visual guidance, when the switching point criteria would be understood. For example, by a clear reduction of speed tracking error, haptic guidance could be faded out. Also a clear increase on the coordination performance could be a triggering event to stop teaching so frequently on the joint domain. Also motivation, focus and engagement parameters could be a good informative cue for an automatic system to make a transition to a transparent mode. By playing with duration and intensity of each of this phases (namely, guidance versus freedom and joint based versus full motion learning), a perfect training workflow could be achieved.

Note the reader that this work was investigated in healthy volunteers. These results must be critically appraised when applying these principles of training design, to neuro-rehabilitation. Although challenge and therefore engagement to the therapy is increased when support or guidance is removed, most of patients will have no muscular tone to perform the training protocol, negatively impacting their motivation and therapeutic outcomes. As mentioned further in this discussion, the approach to follow in these cases would be "Assist as needed controllers" (see the review [51] for some examples). In this case, when having a self-learning algorithm that adjusts the support, the "Challenge Point" [30] could be tracked and as a result the level of

[1] Except for the decrease in pressure (which is still negative, since they did not seem to feel the exercise as important)

Parameter	Whole coordination	Anatomical coordination	Anatomical haptic	Anatomical visual	Dominant
Motion	9.25%	19.75%	9.50%	7.75%	2
Position	15%	31%	17%	18%	2
Speed	15%	10%	12%	6%	1
Coordination	6%	21%	12%	5%	2
Dynamic C.	1%	17%	-3%	2%	2
Retention	21.81%	30.92%	9.50%	-11.00%	2
Position	35%	44%	24%	6%	2
Speed	11%	13%	3%	-25%	2
Coordination	28%	47%	6%	-20%	2
Dynamic C.	21%	34%	5%	-5%	2
Transfer	10.81%	13.05%	2.62%	14.25%	4
Position	25%	11%	-3%	24%	1
Speed	7%	11%	0%	11%	2
Coordination	13%	15%	6%	12%	2
Dynamic C.	6%	16%	7%	10%	2
Consolidation	0.50%	3.25%	-4.50%	-5.00%	2
Position	2%	8%	-3%	-3%	2
Speed	-4%	2%	-10%	-11%	2
Coordination	4%	3%	-5%	-6%	1
Dynamic C.	0%	0%	0%	0%	1
UserX					
Interest	1.21	0.6	0.32	0.9	1
Competence	0.82	0.5	-0.29	0.2	1
Effort	-1.13	-0.62	-0.62	-0.62	1
Pressure	-0.75	-0.4	-1.15	-0.8	3

Figure 4.4: Recapitulation table for comparing hypothesis. For all parameters the positive values relate to percentual improvement of a certain feature, except for the User experience (UserX) where positive values imply increase and negative values a reduction of the specific marker. The summary headings with gray background intend to show the mean overall score (of all features) for a certain time frame comparison: after training(motion), in long-term retention(retention), for the transfer motion or between end of training and long-term retention(consolidation). The number and the bar symbolize the "wining" group in each category. [2]

support provided could be tuned online. Additionally, the break-down of the motion, seems still transferable to the neuro-rehabilitation scenarios. However, it seems recommended, from our results, keeping means of re-composing the motion haptically. One possible solution is the use of exoskeletons, which allow training focused in the joints and in the full motion (even with end-effector focus). The sensory information provided, both in haptic and visual manner, would probably increase the retention and consolidation of the task learned, which does not necessarily need to be a sport motion, but can also be an ADL (Activity of Daily Living). One point to be further worked out is the motivation aspect of the therapy, since several volunteers complained about the tedious task and length of the protocol. A possible way of circumventing this limitation would be "Gamification" techniques and better metaphors and gamified setup. In our study, for example, focusing on the rugby motion, the rendering of a ball and ball's flight as a result of our movement, together with a distance score and ranking of maximum distance achieve by other competitors would have made the setup considerably more appealing and amusing. All these and other aspects that are susceptible of improvement should be investigated in future works by the researchers on the field.

In the following this work is wrapped up, pointing out the pursued achievements and missing points and giving the author's thoughts on how to walk this path further down.

[2]Values in this table are just a summary/repetition of the previous values (shown in previous tables). A 4 group comparative rank is provided in the last column, which shows the *outperforming* group for each criteria.

4.5. Other interesting facts

There are two additional interesting points to discuss in terms of study design. One of them is the selection of a specific joint break-down schema; in this study the upper arm (i.e. shoulder motions) and lower arm motions (elbow extension and pro-supination of the forearm). One could have selected another schema, such as axial rotations (pro-supination and internal-external rotation of the shoulder) with angular rotations (elevation and abduction of the shoulder and elbow extension), which have maybe more affinity in terms of motion type. However, this decision was done based on the previous studies on the topic, such as Klein's paper [42] or other studies on the field of human motor control such as [15, 16]. In the last mentioned studies of Dounskaia and colleagues, they hypothesize that motor learning and control might be a hierarchical process where different learning processes and motor control mechanisms happen at different levels of organization. In this regard, they also propose that the control of *child joints* such as the elbow w.r.t. the shoulder, happens in an adaptive manner and influence from the motion of the *master* joint (i.e. the shoulder). This would encourage us to separate the motions of the shoulder and the elbow to later joint them together in order to provide this specific way of learning. In such a way, the tuning of the parameters for elbow control would happen in the re-composition phase of our study, while the learning of motion pattern of each segment would happen independently. The coordination pattern, to our intuition happened therefore in the complete motion practice, which is substantiated by our results, where groups 1 and 2 (i.e. "Whole Coordination training" and "Anatomical Coordination training") outperformed in such metrics. However, this cannot be fully claimed under the light of our results, provided the fact that we did not use a different break out mode for comparison. This is an interesting claim to investigate though in further experiments. For the further experiences reading upon [5, 6] is highly recommended.

Additionally, in this study, a certain number of volunteers (8 in total, 2 per group) where asked to perform the Long-term retention phase once more. This additional practice was done with the help of first person view, instead of first person view. The results could not be analyzed, due to time constraints. However, most of the subjects reported a higher "ease to perform" and also their results, to eye inspection (from the final feedback provided) looked outperforming the third person view. This phenomenon is in agreement with [77] where taichi training was provided by first person view in comparison with a third person view avatar. In this study, also, the first person view outperformed third person view, hypothetically due to a more level of detail in the perception of the joint poses, due to a closer look into each of the joints. Despite the scientific evidence and the preliminary pilot tests performed in advance of our study, this method was discarded due to the Cybersickness effects that were reported by pilot participants.

4.6. Limitations of the study and outline

In this study, interesting results have been investigated and discussed. However, the significance of these results is limited by the shortcomings in the design and implementation of the study.

Limited sample size Firstly, the sample size was limited (16 subjects) with a clear bias of the genre of the subjects (mostly men). This makes us recommend caution when interpreting the results. Additionally, due to time limitations, a proper analysis of the affinity of the subjects to work with robots or use virtual reality setups could not be assessed, which might have had an impact in acceptance of the technology and therefore emotional bias towards the training they were provided with.

Effect of the robot compensation on motor learning Another important aspect of this work is the new control approach underlying the motion of the robot. A DOB (explained in Appendix) was used to provide a compliant control of the interaction human-machine. This gave a, "subjectively" judged, more transparent interaction. However, no data is provided to support this. Therefore a direct comparison with [42] cannot be done to the full extent. This was a known fact, and more studies have to be conducted in ARMin 5 in order to quantify the effect of mis-compensated dynamics of the robot. Bear in mind that the system is a high inertia piece of hardware which "tries to follow" the motions of the human. The reliance on force information and the performance of the motors and control system are a weak chain element of the system. A transparent interaction is of key importance to state that the results presented in this work are due to motor performance, instead to adaption to the system or measured robot dynamical effects. For example, several subjects complained about the motion of axis 3 (i.e. Internal/External rotation of the shoulder), as "being laggy". This is because several design and tuning decisions were made, which stay on the subjective perception of the researchers (for more information see Appendix on nominal inertia). No joint-by-joint analysis could be done for the limited time available for data processing. This is a desired task to be conducted, which could bring some more information about the transparency of the ARMin 5 system.

Similarly, two other hardware problems affect, very likely the performance of all groups (as a random effect): the shoulder actuation and the pronation supination linkage to the body.

Shoulder alignment First, the shoulder is anatomically a very complex joint to model and replicate [84]. The shoulder actuation in ARMin has been studied and results reported in several studies [58][59], together with its limitations. The problem has its roots in the non constant position of the Centre of Rotation (CoR) of the glenohumeral joint, which moves along the scapulo-thoracic axis and displaces on the horizontal plain. This fact impacts on the motion of the robot in the sense that reaction forces between the human and the robot arise, because of the fixed CoR (or adaptive [58]) CoR of the joint. This causes discomfort on the subjects, limiting their commitment to the task.

Control of pro-supination Additionally, a decision was made to increase the performance of the robot, in terms of DOB performance. The hand module of ARMin 5 was removed for this study. This made all torsion forces, arising from the pronation/supination motion of the forearm, impact on the axis 5 (i.e. forearm sensor). However, the cuff driving axis 5, rigidly connected to the forearm sensor, lacks a rigid connection to subject's arm. This acts as a low pass filter for the DOB input, giving a slightly *laggy* behavior. This, complemented with the negative effect of the sensor drift (especially high in sensor forearm), made the system behave in a resistive way, randomly, in some of the trials of the experiment (depending on the duration of the same). These effects, are assumed to be affected equally for all groups, producing discomfort and frustration, which is not optimal for a study of this characteristics.

Other outcomes to be analyzed Additionally, several outcome measures, apart from the presented in this report were taking, such as forces, questionnaire additional items and other experimental conditions (such as first versus third person view avatar acceptance and performance indexes). This data could not be analyzed since it was outside of the scope of the thesis and the time available. Additional ideas, such as testing the transfer to real practice (i.e. quantification of skills gained in a Motion Capture system environment with real ball throwing) was discarded, given the time limitations. Despite the limitations, some interesting results could be characterized and reported.

5
Conclusion

This project was set up for, eventually, conducting a motor learning study. The research question was motivated by the curiosity about the effect of full-motion haptic guidance in order to learn a complex motion. The antecedents of this study [42][49] had investigated the effect of breaking down a motion into subcomponents. However, the motion was always shown as a whole, all the time. The innovative twist of this study is the investigation of removing this full-motion demonstration, understanding then what is the contribution of the haptic information gathered by the subjects while training in a "part-whole transfer" paradigm learning setup. The employment of visual feedback alone allowed the researchers to also understand the importance of haptic feedback in learning speed profile. Additionally, the partial replication of [42] in what relates to anatomical breakage of a motion allowed me to confirm their results and hypothesis.

The results might be valuable for the field of motor learning. First of all, the acquisition and prevalence of knowledge relating the shape of a movement, are improved by anatomical visuo-haptic training and visuo-haptic coordination training, when compared to whole training and no coordination training, as it was already stated by [42]. Additionally, speed profile of a motion is better learnt when the full motion is practice in a visuo-haptic environment more times, rather than only visually or taught in its components. The coordination patterns are replicated more accurately by the visuo-haptic anatomical coordination training group, probably due to the more compartmentalized and solid skills acquired which build up from minor to more complex motor learning patterns. Recall of the skills is bolstered by anatomical decomposition and recomposition (i.e. coordination training) when this one is done visuo-haptically, due to a phenomenon already studied in literature as *consolidation*[24]); which was more prominent in the visuo-haptic anatomical coordination training group. The transfer of the skill happened in all groups, although paradoxically it was accentuated for visual only or whole visuo-haptic coordination groups. This might be due to the compatibility of the feedback modes, or to the fact that transfer motion was substantially different from the target motion, including different speed profile, shape and coordination patterns. Finally, the guidance hypothesis[70] and the challenge point[30] theories, were confirmed in terms that more guided users perceived themselves as performing better and experienced more enjoyment (using less effort), while the performance suffered from this lack of commitment. On the contrary, the group who had a more progressive training, in the sense of building up the skills (i.e. visuo-haptic coordination training, group 2), had a tougher training routine, but achieved better levels of performance and retention.

These results can be used to improve current complex skill training systems in both sports and other complex skills which require joint coordination (surgery, etc). Given the fact that motor skills acquisition and recovery are related by several aspects[46], might it be the case that transfer of this knowledge could benefit neuro-rehabilitation therapies. This has to be confirmed though by a study with stroke survivors, though. However, first a bigger sample population should be recruited for a being able to confirm and consolidate (with more statistical power) the mentioned findings.

The fact that more practice of the whole motion, visuo-haptically, improved the speed profile learning, might be a clear sign that adaptive hybrid systems are desired. Given the evidence that motor learning skills acquisition is a function of: the task type [53], the level of skills of the practitioner [19][52][74], the cognitive load to which they are subject(e.g. the amoung of information that has to be processed [80], where the focus is put[88] or the emotional status of the subject[19]; it is important that these new training systems can meter and track the interest variables in order to adapt themselves to keep the users in the "flow"[13].

For example by automatically metering and understanding the phase of learning, skill level, emotional status and cognitive loading that characterize a given practitioner at a certain instant the system could regulate the environment (i.e. number of visual and haptic stimuli provided) so that the subject can progressively "feel" an increasing number of parameters which would trigger error-based and reward-based [35] mechanisms in an optimal way. Some guidelines are provided in [39], which could be applied to the field of motor learning by encompassing them to the aforementioned approach, based on our results.

This work, in summary, contributes to the field substantiating the "part-whole transfer" paradigm and harmonizing its postulates with the "Task-Oriented training paradigm". This is because both practice of the broken down motion and the complete motion are required. Additionally it substantiates findings in favor of visual and haptic feedback combined in a multimodal manner. The findings in terms of haptic feedback usefulness support the use of robots in motor learning studies and training protocols for healthy participants. Additionally, the results regarding engagement when the support is removed, support investigation on more transparent devices which allow free practice of a motion.

All these findings have an impact in the design of future motor learning studies. Also certain implications for the field of neuro-rehabilitation can be drawn from this thesis. For example, although transparent operation of the exoskeleton to freely move and perform a motion is necessary, the robot could be programmed to provide an intelligent "assist-as-needed" program which can balance the provision of haptic cues and visual-based free practice, adapting to patient's needs. The strength of the results achieved by Group 2 (in this work also named as "Anatomical coordination training"), strongly supports the use of exoskeletons, since this are the only systems, up to date, that can provide haptic feedback both at the joint level and during a full motion (similarly to end-effector actuators). However, all these statements have to be revisited in a new study where all the limitations, mentioned in section 4.6, are addressed.

In the appendix A.3, the academic progression of this project is evaluated in work-packages and an overview of successes and items that could still be done is provided.

6 Acknowledgements

This research project would not have been possible without the support of two scholarships I enjoyed: Fundación Barrié and IDEA League grant. These grants covered my maintenance during my studies in Delft, at TU Delft and in Zürich, during my exchange period which lasted for 1 year. I am grateful to these two networks of excellence which trusted me to push forward Spanish and European research boundaries.

The robot used for this study has been result and tool of several doctoral and post-doctoral student with whom I shared a very intense and productive period of my life. I would like to personally thank Dr. Aniket Nagle, for his time expend on my training for developing serious games. The help of Kilian Baur for his kind recommendations and experience which avoided me many mistakes. I will not forget long nights fighting with our respective robots. For using the new engineered system, ARMin V, I would like to thank Fabian Just, who kindly shared his time and resources with me. I hope I have contributed to his vision with my work. Mathias Bannwart has given me always support with his good insight on the topic of motor learning and applications of exergames to gait rehabilitation.

All project would have not been taken place without the efficient and professional work of Marco Bader, Michael Herold-Nadig and Nicolin Lutz. I have gained very valuable and numerous practical topics related to implementation and safety aspects working hand in hand with them. Thanks for your time and support. For their valuable insights on study design and statistical analysis I would like to thank Nina and Jakob, the correspondents from *Seminar für Statistik (SfS)* at ETH Zürich.

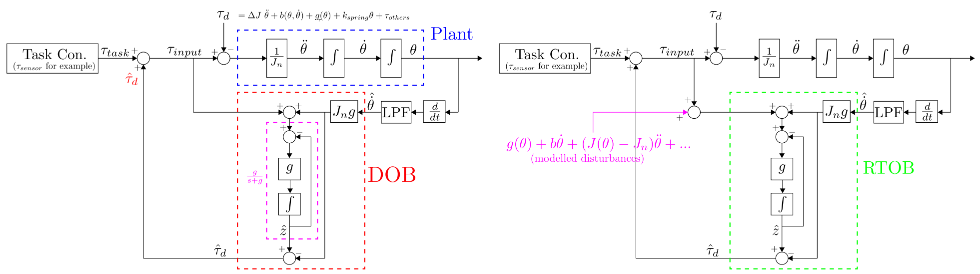
For all help in the study design and management, I would like to thank Anja Kühnis. She supported me very professionally during her internship by organizing all study scheduling and participants recruitment, she built all questionnaires, managed the data acquired and conducted the experiment. Additionally, she brought very nice ideas and contributions, which allowed me to make a nice study in a restricted time. I feel very thankful to her support and to how her attitude and commitment permitted conducting a study which I believe is of interest to the community. The help of Zsombor Kalotay and Özhan Özen in the technical aspects (Unity 3D debugging and counseling and Disturbance Observer implementation, for visual and haptic environment respectively) was key to achieve a good level of performance of the setup during the experiment.

Finally I would like to thank Prof. Riener and Dr. Wolf, for their nice and welcoming attitude when I applied to Sensory-Motor Systems Lab. I have enjoyed greatly my year at this team, I have grown as a person and this experience has constituted a very important point in my life which has been decisive for my current and future endeavors as biomedical engineer.

A
Appendices

A.1. Robot control

Robot in transparent mode



(a) The DOB (Disturbance Observer)

(b) The RTOB (Reaction Torque Observer)

Figure A.1: The DOB (Disturbance Observer) and similar RTOB (Reaction Torque Observer) block diagrams are shown in the figures above, respectively. ARMin V control structure of a single motor (i.e. joint) including velocity based DOB. J, J_n and θ are the real inertia, nominal inertia and the angle of the axis, respectively. Note that the estimated disturbance that is feedback to the system at iteration k, $\hat{\tau}_d$, is estimated at iteration $k-1$ of the control loop. This figure is adapted from Master Thesis of Özhan Özen with permission of the author.

Derivation and dynamics of the observer

This disturbance observer is designed at each single joint of ARMin (can be seen in appendix A.1), independently from each other, with the intention to estimate for the generalized disturbance (τ_d) at each axis. Disturbance for each axis is a broad concept that covers all kind of undesired torque/force on the axis; gravity, friction, model errors, undesired/unknown part of the inertia or motor torque constant, inertial coupling terms coming from the motion of the other axes, sometimes the interaction forces, etc. In other words, anything which is fed in as an input to the observer (thus, except the speed data) is a part of the τ_d.

An assumption made is that disturbance τ_d changes slowly wrt. the system dynamics; which means $\dot{\tau}_d = 0$.

An intermediate variable z, is selected as;

$$z = \tau_d + l\dot{\theta}, \; l = cost > 0 \tag{A.1}$$

Taking derivative and projecting to the system dynamics results in;

$$\dot{z} = \dot{\tau}_d + l\ddot{\theta} = \frac{l}{J_n}(\tau_{input} - \tau_d) = \frac{l}{J_n}(\tau_{input} - z + l\dot{\theta}) \tag{A.2}$$

Since J_n, $\dot{\theta}$ and τ_{input} are known, an observer for z variable can be designed with similar structure as in eq. (A.1) and eq. (A.2).

$$\dot{\hat{z}} = \frac{l}{J_n}(\tau_{input} - \hat{z} + l\dot{\theta})$$
$$\hat{z} = \hat{\tau}_d + l\dot{\theta} \tag{A.3}$$

The "ˆ" notation represent the estimation of any variable. Please note that $\dot{\tau}_d = 0$ does not mean that $\dot{\hat{\tau}}_d = 0$. Taking derivative of $\hat{\tau}_d$;

$$\dot{\hat{\tau}}_d = \dot{\hat{z}} - l\ddot{\theta} \tag{A.4}$$

Substituting eq. (A.3) to eq. (A.4) gives us the observer dynamics for the disturbance estimation;

$$\dot{\hat{\tau}}_d + \frac{l}{J_n}\hat{\tau}_d = \frac{l}{J_n}\tau_d \tag{A.5}$$

Estimated disturbance is the output of this non-linear first-order filter. Estimation error e_{est} is;

$$\dot{\tau}_d - \dot{\hat{\tau}}_d = -\frac{l}{J_n}(\tau_d - \hat{\tau}_d)$$
$$\dot{e}_{est} + \frac{l}{J_n}e_{est} = 0 \tag{A.6}$$

Selecting l as $J_n g > 0$ make the estimation, a smoothed version of disturbance using a first order filter;

$$\hat{\tau_d} = \frac{g}{s+g}\tau_d \tag{A.7}$$

Implementation
Considering eq. (A.7),

$$\hat{\tau}_d = \frac{g}{s+g}\tau_d = \frac{g}{s+g}(\tau_{input} - J_n\ddot{\theta}) = \frac{g}{s+g}(\tau_{input} - J_n s\dot{\theta}) \tag{A.8}$$

Manipulating the equations yields in;

$$\hat{\tau}_d = \frac{g}{s+g}(\tau_{input} + J_n g\dot{\theta}) - J_n g\dot{\theta} \tag{A.9}$$

, where, in this study,

$$J_n^{5x5} = diag\Big(2.7031 * 0.35, 1.7401 * 0.5, 0.2238 * 0.8, 0.2499 * 0.7, 0.0967 * 0.2\Big)\Big[\frac{N \cdot m}{rad/s^2}\Big]; \tag{A.10}$$

being the second term of each element a scaling factor tuned according to designer's criteria for a better performance (i.e. stability versus transparency trade-off). Also being,

$$g = (g_1, ..., g_5) = (60, 100, 220, 300, 700)[rad/s]; \tag{A.11}$$

for maximum bandwidth affordance.

Which is the implementation of the observer used in many systems, including ARMin joints. For more detailed information, please refer to [44, 62].

Switching controllers for the experiment

- A DOB is designed for each axis of ARMin. By applying this algorithm the system is controlled in the acceleration and behaves as a double integrator.
- The DOB provides the system with a higher transparency and it is the underlying controller running in ARMin. Any other functionality is implemented in a task controller, which should be designed to control the acceleration for difference tasks, as it ;
  - Explicit acceleration control (or zero-force control in other words)is achieved by making τ_{task} equal to $\tau_{sensors}$. It is important to notice that the sensor data is driving the motion of the robot rather than the real physical force applied in this mode. Thus, robot cannot be moved without touching the sensors. This way, any other contacts on the machine (out of the sensed areas) are seen as disturbances and a part of τ_{other}. Furthermore, real Jacobian (i.e. kinematic structure of the system) does not matter anymore.The mapping between F_{sensor} a τ_{sensor} is the new "Jacobian".

- If position control is desired, any desired second order dynamics ($\ddot{e}+K_d\dot{e}+K_pe,\ e=\theta_{ref}-\theta$) can be enforced by ($\tau_{task}=J_n[\ \ddot{\theta}_{ref}+K_d(\dot{\theta}_{ref}-\dot{\theta})+K_p(\theta_{ref}-\theta)\ ]+\tau_{int}$), where τ_{int}[1] is the measured interaction torques and τ_{task} is the intended commanding torques for a given motion, dictated by the control gains (i.e. K_d = $[100]_{5x1}$ and K_p = $[20]_{5x1}$) and the nominal inertia defined for each joint of the robot (i.e. J_n). This also applies if velocity control is desired. In this thesis, a trajectory control (enforcing PD law, i.e. position and speed) is used .

- Observer gains g, change the rate of the convergence of the estimation. Behaves as a bandwidth for observer. The higher the gain is, better, theoretically, the estimation is. In practise, it is limited by the noise. System starts to vibrate in response to the noise if g is so high. Filtering the velocity data is useful but can bring instability due to delay if filtered too much. Tuning process is trial and error. In order to increase g further, to increase the performance, noise should be suppressed without introducing delay. Also, increasing the sampling rate of the system allows both better filtering of noise and usage of higher g values, which was the case in this experiment (raising the speed from 1kHz to 1.8kHz).

- J is the real inertia of the system which is dependent of θ. J_n is nominal inertia (constant in ARMin) which is used as a design parameter. DOB enforces the dynamics (double integrator) with J_n to the system. For example, if this value is selected as lower then real inertia and constant for one axis, that axis will move like it has lower and constant inertia. However selection of this parameter is not completely arbitrary due to stability problems. For further information please refer to [44].

[1]Note that τ_{int} is given a positive sign just as a convention, i.e. it depends on the convention followed when defining contributing or resisting torques at each joint.

Performance of the proposed controllers

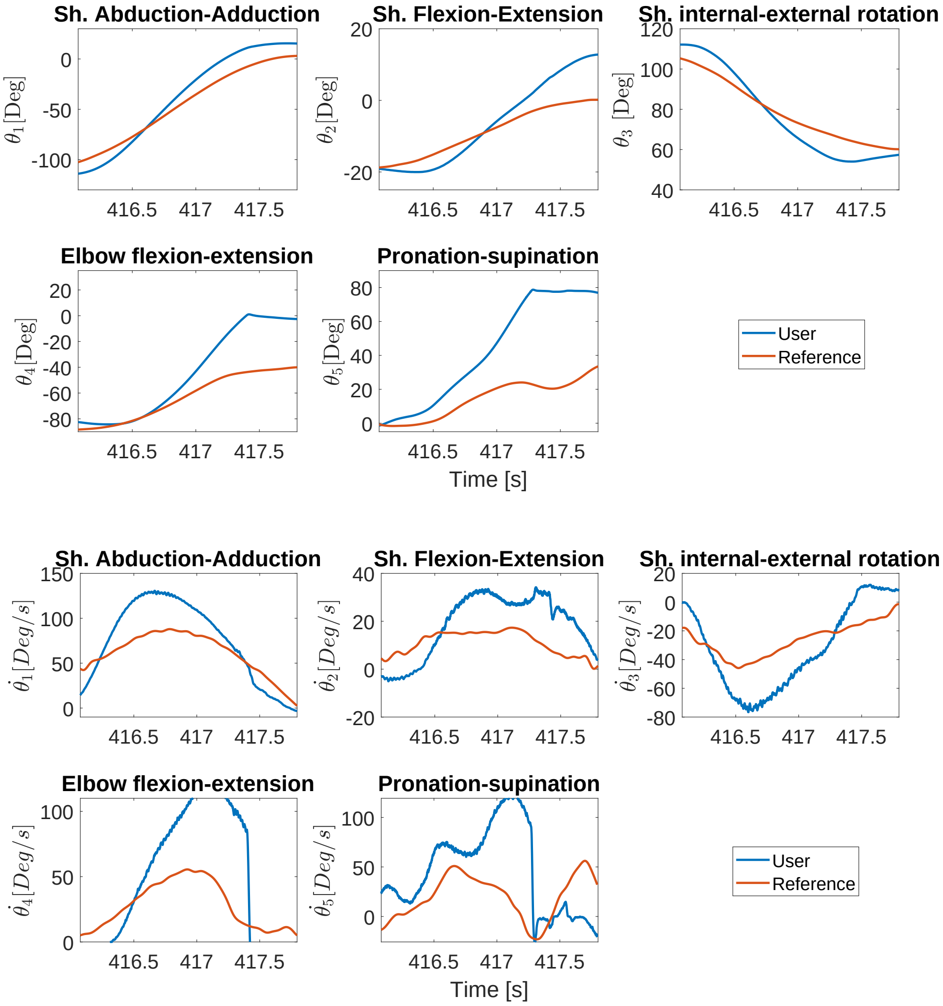


Figure A.2: Motion tracking without guidance. User was actively cooperating.

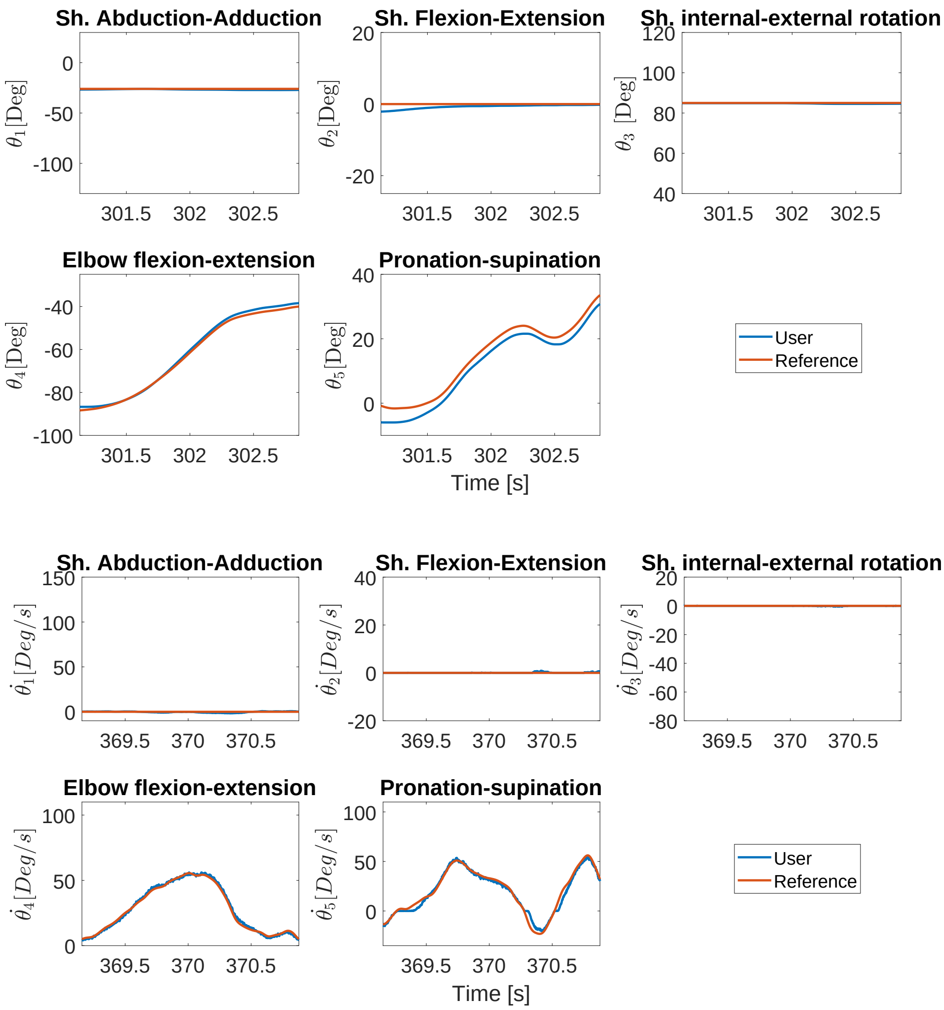


Figure A.3: Motion tracking with forearm guidance. User was actively cooperating.

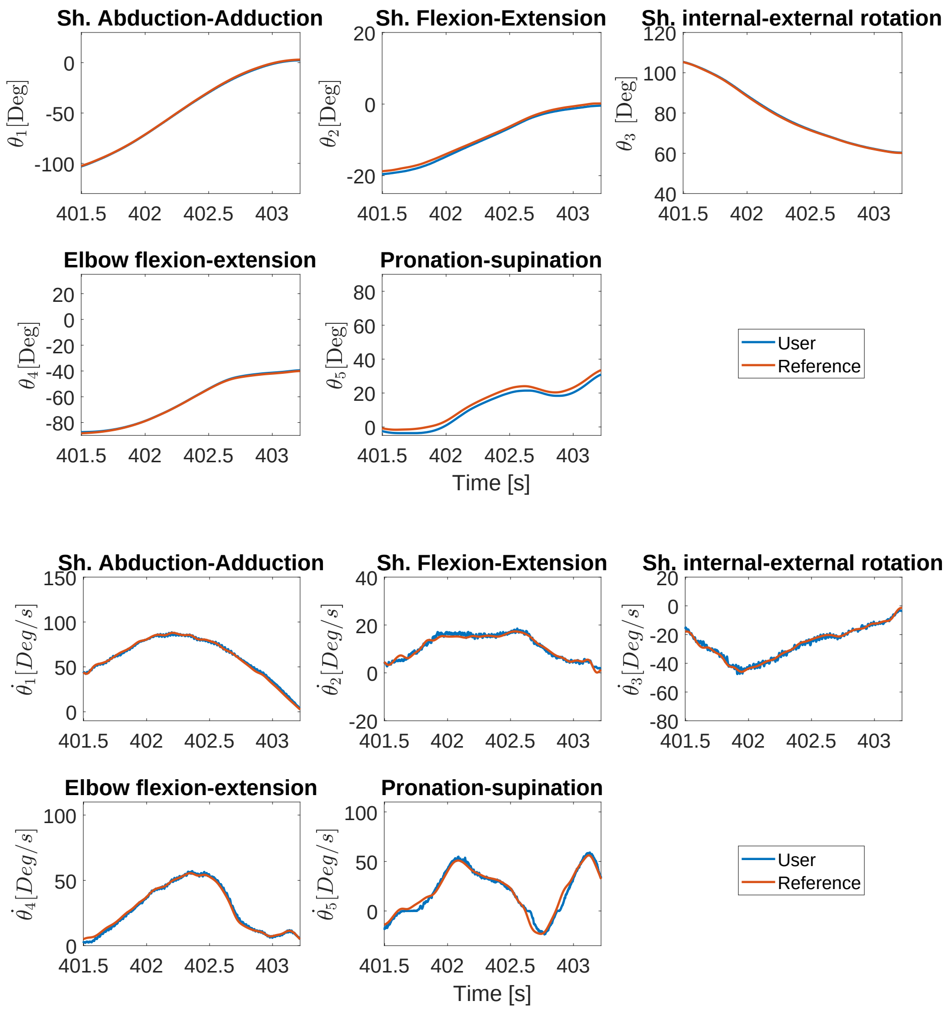


Figure A.4: Motion tracking with full-motion guidance. User was actively cooperating.

A.2. Sideworks

For completion of this work, several side gaps had to be filled, which turned up during the planning and implementation of this project. Several of them were related to routine maintenance of the robot, which were mainly addressed by the staff at SMS Lab who kindly supported the development of this project. Some other issues, here mentioned in detail, required a more thorough attention and some more special care.

Among all tasks needed for the setup to be *up and running* some are of remarkable interest:

- **Correction of kinematic transformations of ARMin V:** The kinematic translations block (i.e. forward kinematic) and Jacobian was re-coded following the Denavit-Hartemberg standard in order to *boost* the performance of the motion controller commanding the exoskeleton. This work was done jointly by Özhan Özen and myself.

- **Upgrade of real time Operative System (OS):** After including the full version of the safety layer, implemented by Fabian Just, we notice that the computation power required had dramatically increased. This implied that either the DOB (mentioned in appendix A.1) should run slower (with a subsequent deterioration in the *transparency* of the robot, due to a reduction of the effective controllable band-width) or, alternatively, the system would end up in crash-downs when the time of execution would near the maximum allowed for real-time execution (1 ms for 1kHz). To prevent both unwanted effects, the system was upgraded to a later version of the OS, Simulink Real-Time ®2017a. This allowed for a more refined and efficient code compilation, allowing an execution power boos up to 1.8 kHz. This allowed the system to run with an acceptable performance, fitting still in the execution cycles all calculations required for ensuring safe operation.

- **Update of ARMin OS and communication protocol:** As a side-effect of the upgrade of the OS for the real time system, the communication protocol and ARMin OS system (custom-made system architecture with classes which allow for correct synchronous and asynchronous communication) were to be fixed for the new setup. A simple upgrade of the compiled libraries for 64 bits was required, which solved all communication issues. This work was jointly done with the support of Zsombor Kalotay.

- **Fine tuning and re-formulation of the safety layer:** Due to the highly dynamic nature of the motion here studied, some torque, joint speed and RoM of joints had to be re-adjusted. Additionally, the maximum speed of the end-effector was replaced by a maximum *speed to the face* algorithm which allowed high speeds which were non-colinear to the vector defined between face and hand. This allowed safe operation and execution of the proposed motion. Finally, of big importance, in cooperation with Özhan, a reaction force observer was designed and implement, which allowed the computer to foresee the interaction forces expected in the sensors. This was required by Michael Herold-Nadig, electrical and safety engineer at SMS Lab, in order to provide redundancy in the force-sensing, therefore making the safety layer sensitive to force-sensor failure. A threshold *force mismatch* was allowed. Above this level, the robot would identify the interaction force as excessive or erroneous and safely shut the system down.

- **Motion recording toolbox:** As a requisite for implementation of *any* trajectory (fitting in the robot kinematics) in ARMin, a special custom-made applet was coded that could convert a joint based or end-effector based trajectory *piece* into a spline that could be executed in the exoskeleton.

- **Humanoid avatar:** As part of the visual interface offered to the practitioners for sport's practice, a humanoid avatar was rendered that would be compatible with ARMin kinematic structure. Fine tunning of the *rigging* of the avatar was done so that the motions would map 1 to 1 to the robot motions. The code developed for the motion control of the virtual avatar is built such that eventually hand and wrist actuation is implemented easily.

- **Realistic rugby game scenario:** This game scenario was donated by Zsombor Kalotay for the aesthetical improvement of the game. The adaption was done according to feedback received by all supervisors.

- **Task-success evaluation code:** Although results have not been presented in this document, a code was developed which can compute the task success score of a motion in the terms of the biomechanical principles of sports practice as introduced in [43]. Concretely, projection angle (under 45 degrees), direction w.r.t. the frontal plane (in a cone of 15°with respect to left pointing vector) and minimum spinning speed of 90°per second, were required for considering a motion as correct. This tool can be implemented in the future for a more meaningful terminal feedback which can be better understood as correct *rugby pass*. All criteria were selected upon readout of [79].

- **Ethic's amendment:** In order to make a comprehensive evaluation of the proposed research question and hypotheses, a questionnaire was added (evaluating all kind of User Experience variables, apart from the here analyzed IMI results). Also EMG recordings were taken for 2 subjects. The inclusion of RedCap as recruitment and questionnaire management software was included in the amendment to the corresponding ethical approval. All these tasks were coordinated by myself, with the supervision of my supervisors and the kind and professional support of Anja Kühnis.

- **Data collection for evaluation of different game perspectives:** After reading [77] and arising from different personal opinions about the suitability of using first or third person view, I decided to try answering this question. For this purpose, data was gathered from 8 volunteers (2 volunteers per group) in an additional training session (just after the long-term retention trial). This data, when processed will allow us to make conclusions about the performance increase or decrease when a first person view is used, instead of the here document third person view.

All these side-works and extra data gathered have allowed me to write this thesis, gain knowledge on the topic and, even, in the future answer other research questions. Processing of the full dataset is a pending task which will be conducted, in the future, in the framework of potential collaborations during my PhD in Neuroscience.

A.3. Academic goals, outcomes and future works

This master thesis project was outlined as presented in table A.1.

Task	Milestones	Completion	Date
Literature Research		✓	
	Complex motion	✓	$17^{th}April$
	Feedback modes	✓	$15^{th}May$
	Scheduling of practice	✓	$15^{th}June$
Study design		✓	
	Group design	✓	$5^{th}June$
	Feedback M. selection	✓	$5^{th}June$
	Motion selection	✓	$29^{th}May$
	Protocol layout	✓	$19^{th}June$
Study implementation		✓	
	Controller	✓	$20^{th}July$
	Feedback modes	✓	$27^{th}July$
	Recruitment	✓	$15^{th}August$
	User interface	✓	$15^{th}August$
	Ethics	✓	$1^{st}August$
	Side works	✓	$10^{th}August$
Run experiment	16 subjects (4x4)	✓	$7^{th}September$
Data processing	4 outcomes	✓	$25^{th}October$
	Statistical Analysis	✓	$25^{th}October$
Reporting		✓	$25^{th}December$

Table A.1: Timeline of the project

Within the given time, I have learnt a broad variety of tasks and acquired numerous skills. There were several tasks which I had to learn from null knowledge, such as game development(in Unity 3D®), rendering of models, design of user interfaces and system architecture's design. For this tasks, my background in programming in object oriented languages was crucial as well as Computer Assisted Design tools (CAD). For the development of the required controllers and side works, my background in control engineering was required. Among the side works, the inclusion of a standarized Denavit-Hartemberg model for the kinematics of the robot was implemented in collaboration with Özhan (another student at SMS Lab). This, together with the re-modelling of the control algorithms of ARMin 5 (including the DOB which was the main controller of the system), pushed the performance of the robot, to the point of being able to implement the motion selected (high speed and big amplitude). Also for this purposes, several additional safety features were added, such as "face-direction speed limitations" and "software joint RoM limitations" which allowed implementation of the described motions. This was done in cooperation with Özhan and Michael Herold-Nadig, along several weeks, in order to ensure the safety of our volunteering participants.

With the support of Anja Kühnis, the study experimental design was finished and brought to reality. With the incredible support of Anja, we could recruit a big enough sample size, for my thesis, as well as make an amendment to the existing Ethical Approval, issued by SwissMedic, which allowed us to include several questions and required data for storage. The experiment was carried out by Anja Kühnis with my support and the software and hardware setups which were developed by me and the SMS Lab researchers.

While the experiment was being conducted, the data processing and analysis was conducted, acquiring a modest understanding of the background in statistic necessary to understand the extent of the validity of the measured outcomes.

Another valuable knowledge acquired in the period of this project has been a solid basis of motor learning and control background, together with a solid basis of neuroscience concepts, after completing the literature research part of the project, which is reported in another document. Also the social and "soft-skills" required to work in a multidisciplinary environment in collaboration with therapists and doctors, as well as several types of engineers with different backgrounds.

A.4. Additional figures and tables

Kinematic motion quality evaluation

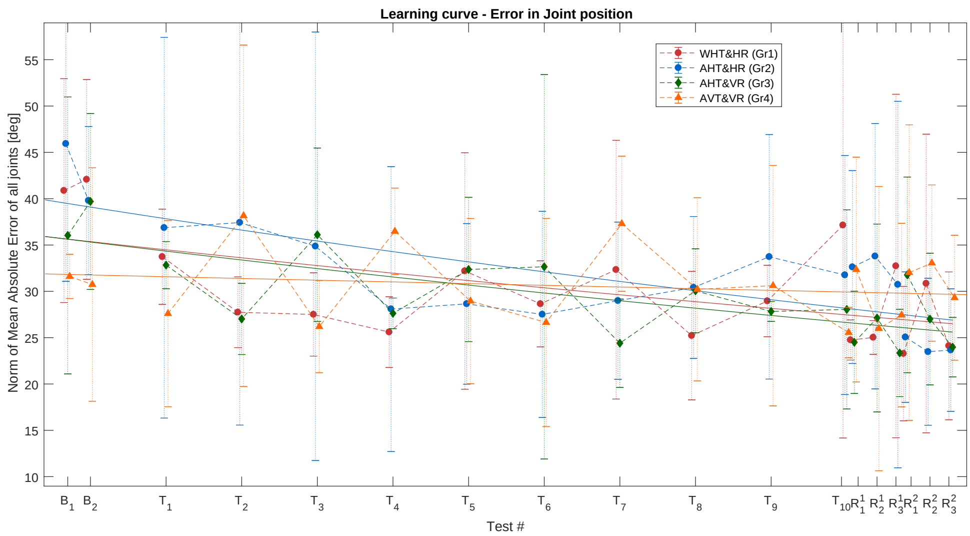


Figure A.5: Evolution of the subject's error in position across trials.Bar graphs are used to provide the standard deviation and Euler fitting is provided for each group, to quantify learning rate.

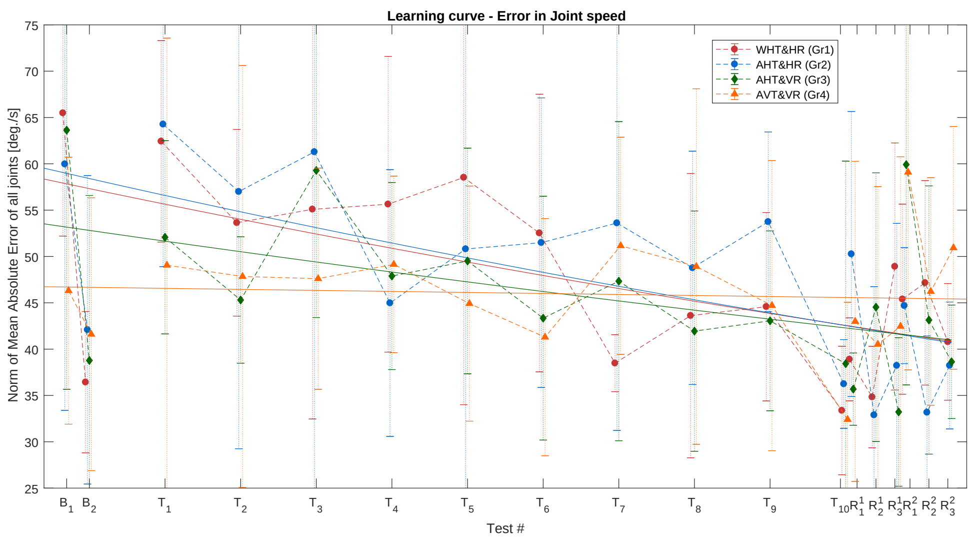


Figure A.6: Evolution of the subject's error in speed across trials.Bar graphs are used to provide the standard deviation and Euler fitting is provided for each group, to quantify learning rate.

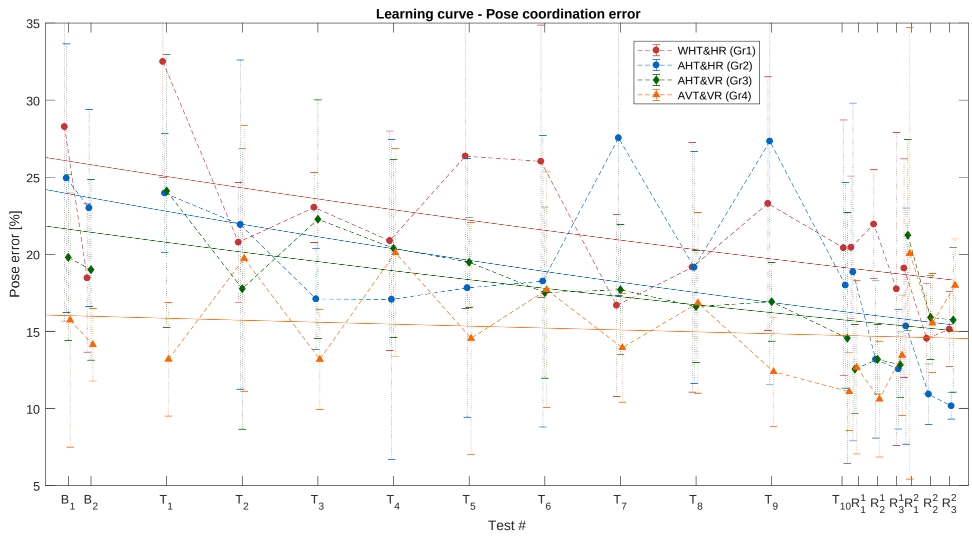


Figure A.7: Evolution of the subject's error in position across trials.Bar graphs are used to provide the standard deviation and Euler fitting is provided for each group, to quantify learning rate.

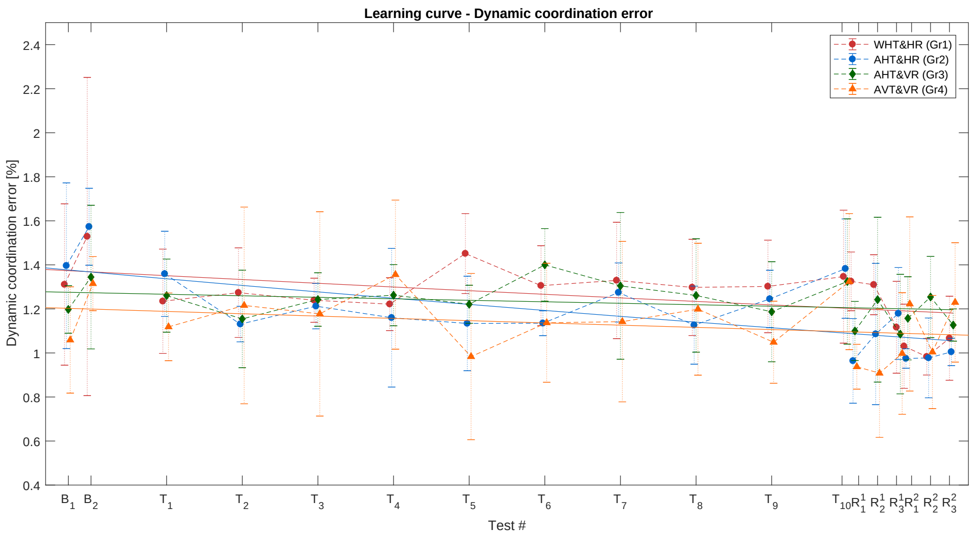
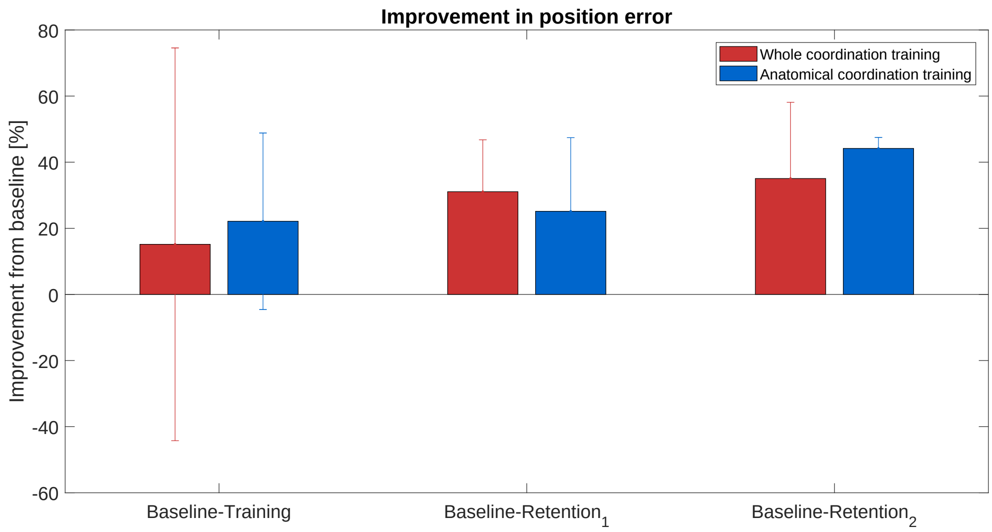


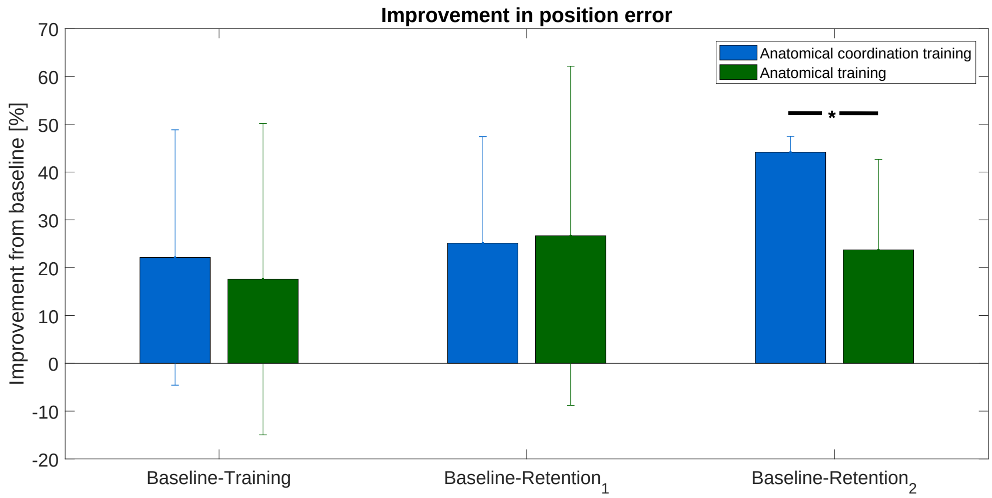
Figure A.8: Evolution of the subject's error in dynamic coordination metric across trials.Bar graphs are used to provide the standard deviation and Euler fitting is provided for each group, to quantify learning rate.

Hypothesis testing

Quality of motion



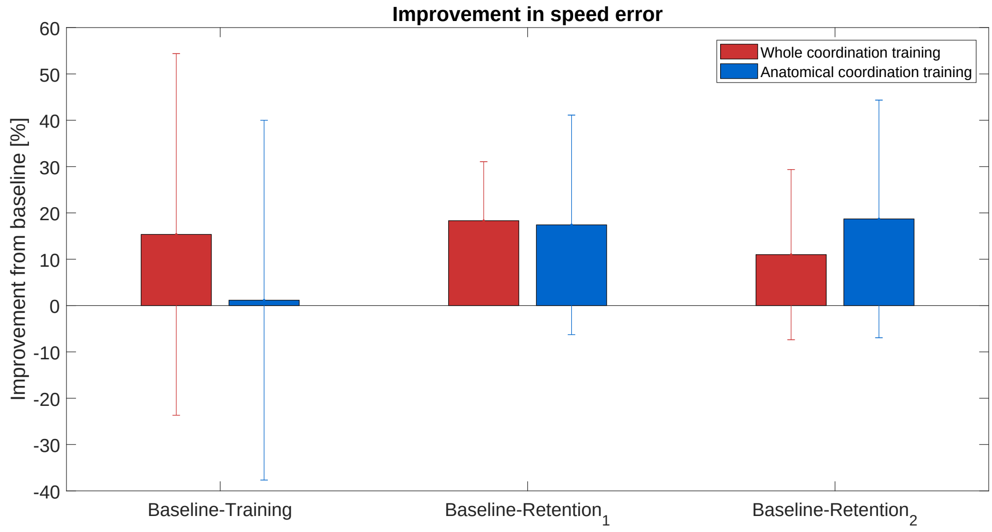
(a) Hypothesis 1 testing: Whole (red) versus anatomical (blue) training



(b) Hypothesis 2 testing: Haptic(blue) versus visual(green) recomposition

(c) Hypothesis 3 testing: Haptic(green) versus visual(orange) training

Figure A.9: Comparative hypothesis testing among study design factors for trajectory shape learning. Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. Significant differences are marked with a star.

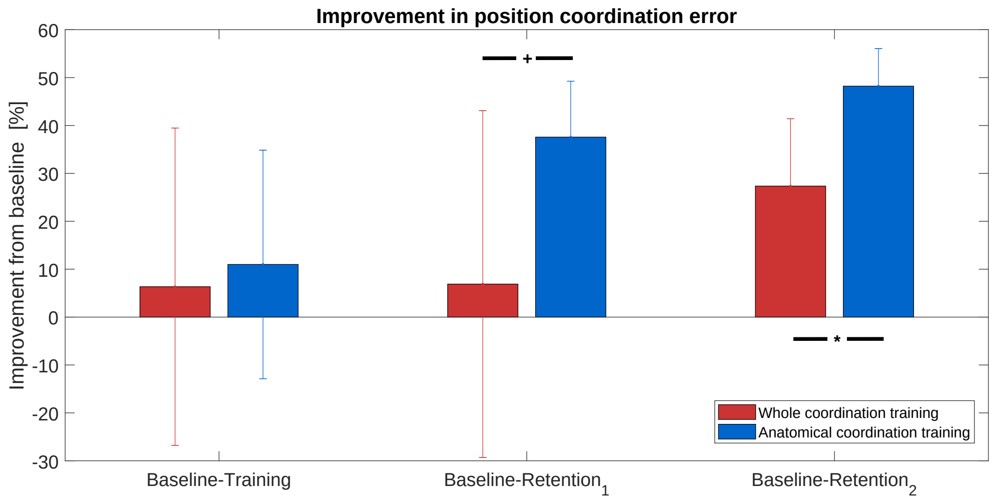


(a) Hypothesis 1 testing: Whole(red) versus anatomical(blue) training

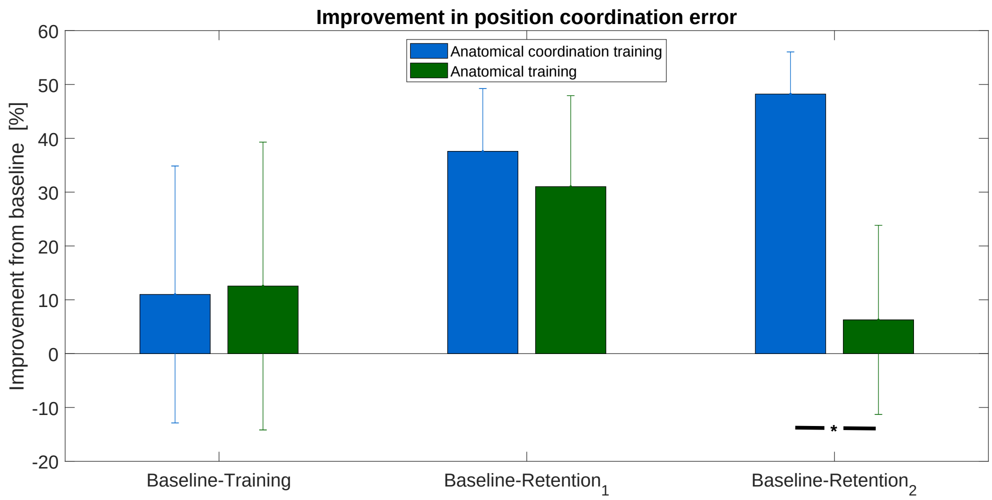
(b) Hypothesis 2 testing: Haptic(blue) versus visual(green) recomposition

(c) Hypothesis 3 testing: Haptic(green) versus visual(orange) training

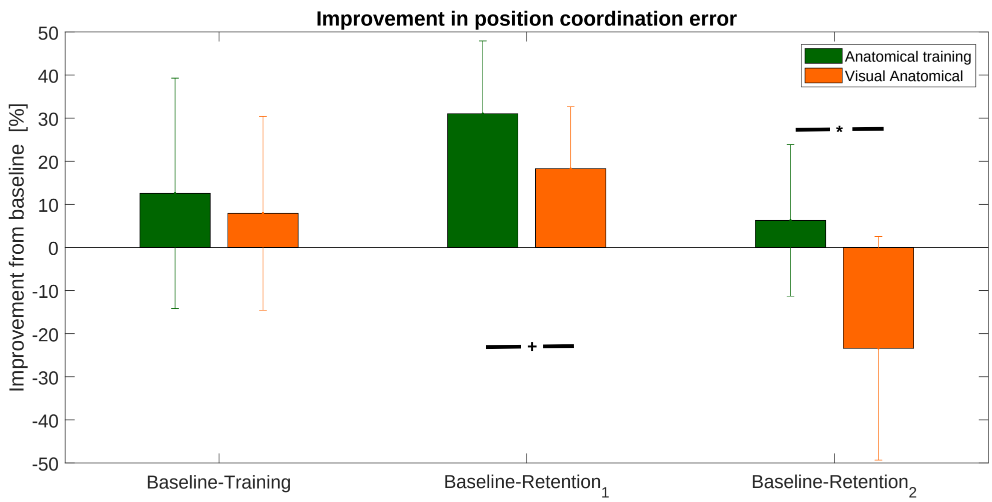
Figure A.10: Comparative hypothesis testing among study design factors for speed profile learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively). No significant differences were found.



(a) Hypothesis 1 testing: Whole(red) versus anatomical(blue) training

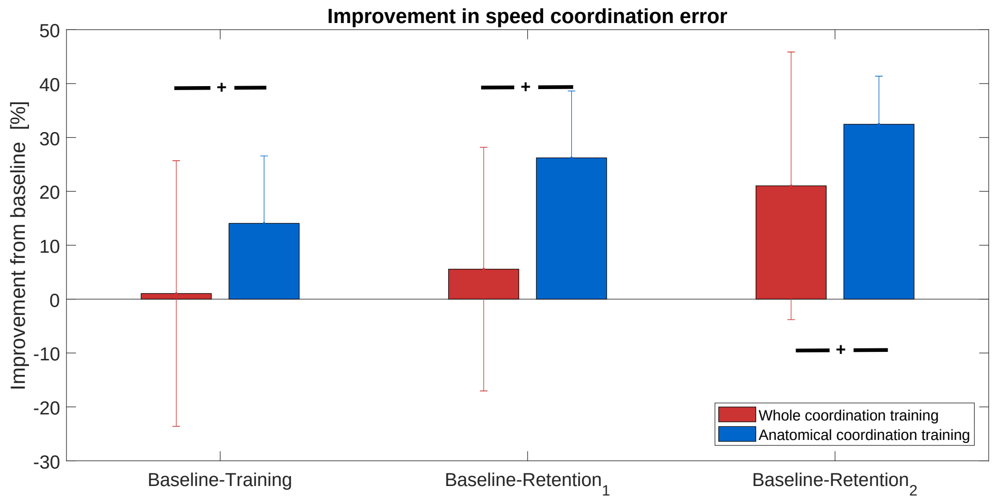


(b) Hypothesis 2 testing: Haptic(blue) versus visual(green) recomposition

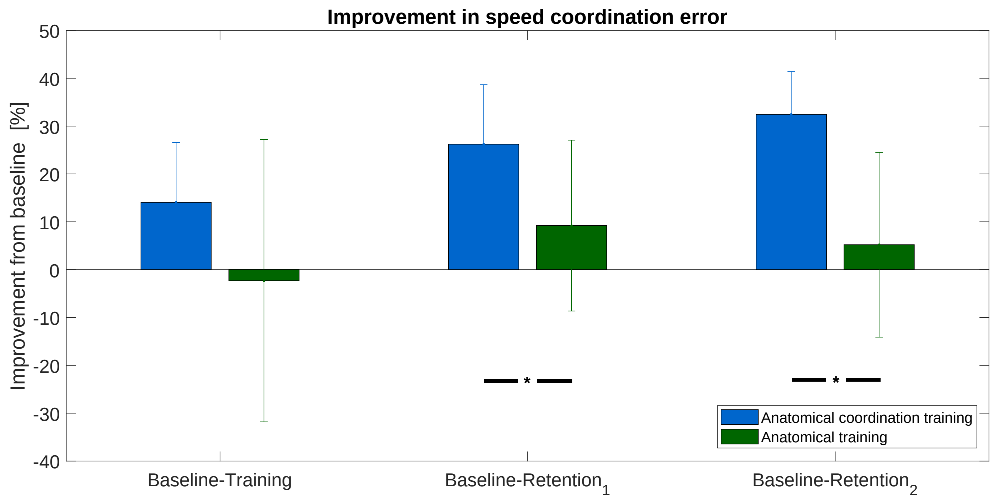


(c) Hypothesis 3 testing: Haptic(green) versus visual(orange) training

Figure A.11: Comparative hypothesis testing among study design factors for static coordination learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. $p<0.05$ marked with *. $p=0.1$ is signalized with +.



(a) Hypothesis 1 testing: Whole(red) versus anatomical(blue) training

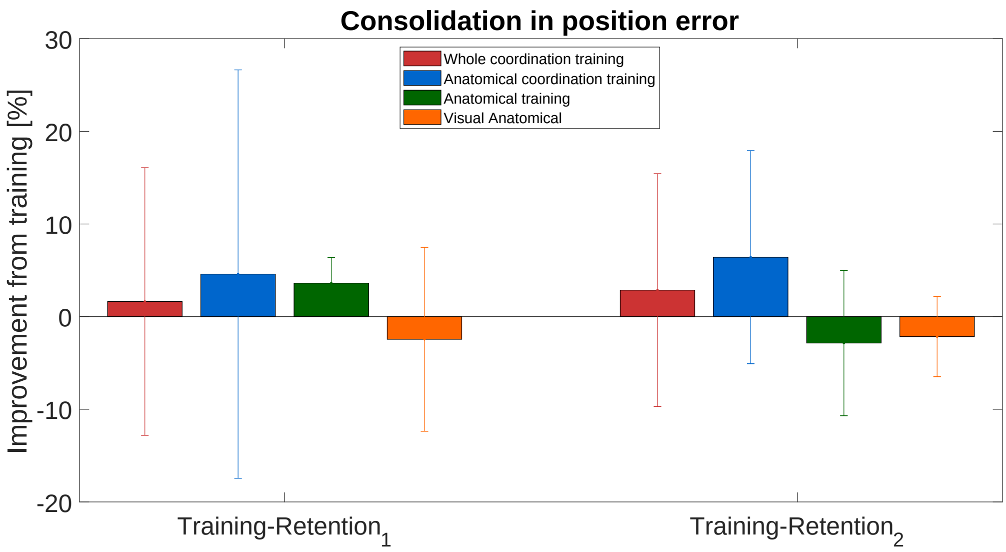


(b) Hypothesis 2 testing: Haptic(blue) versus visual(green) recomposition

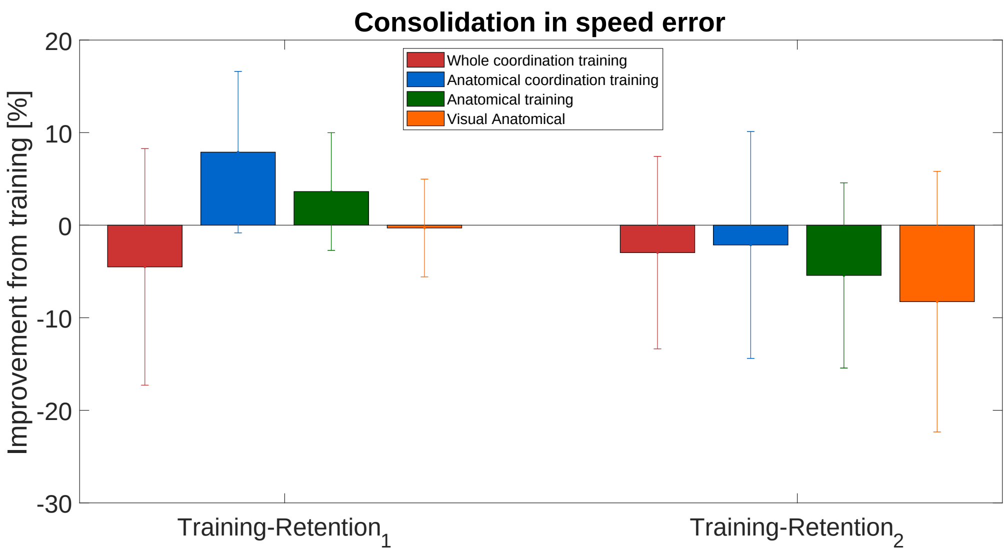
(c) Hypothesis 3 testing: Haptic(green) versus visual(orange) training

Figure A.12: Comparative hypothesis testing among study design factors for dynamic coordination learning: Haptic whole practice versus anatomical practice with haptic recomposition(red and blue, respectively), haptic anatomical practice with haptic or visual recomposition (blue and green, respectively) and anatomical haptic training versus visual training with visual recomposition (green and orange, respectively. $p<0.05$ marked with *. $p=0.1$ is signalized with +.

Consolidation of the skill

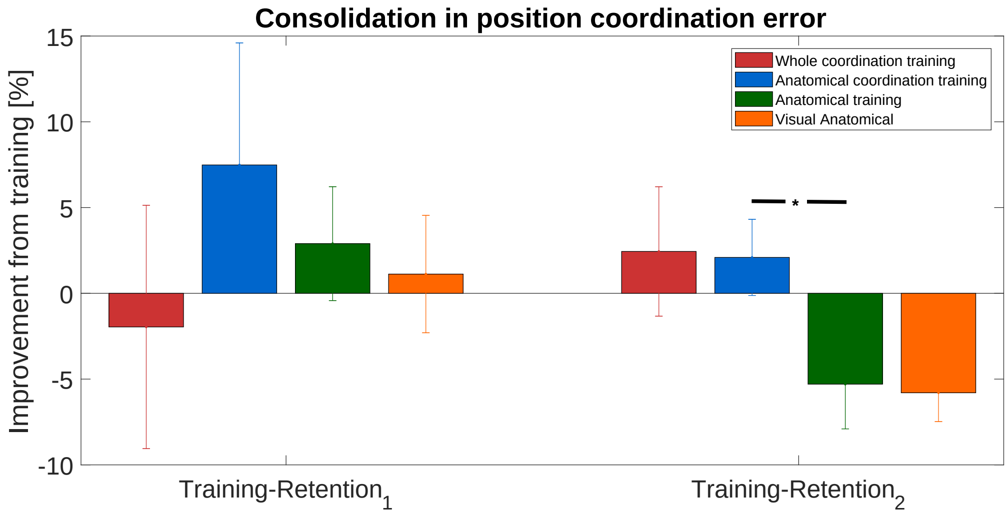


(a) Improvement w.r.t. end of training performance in position (i.e joint angle) tracking as a percentage over end of training skill level.

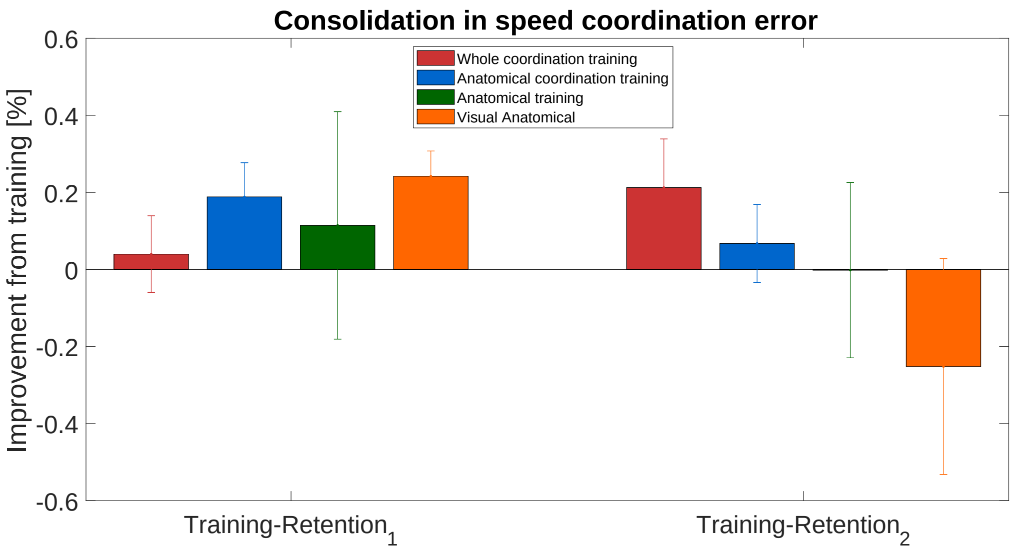


(b) Improvement w.r.t. end of training performance in speed (i.e joint speed) tracking as a percentage over end of training skill level.

Figure A.13: Comparative graph of consolidation of learning level: Shape and speed profile



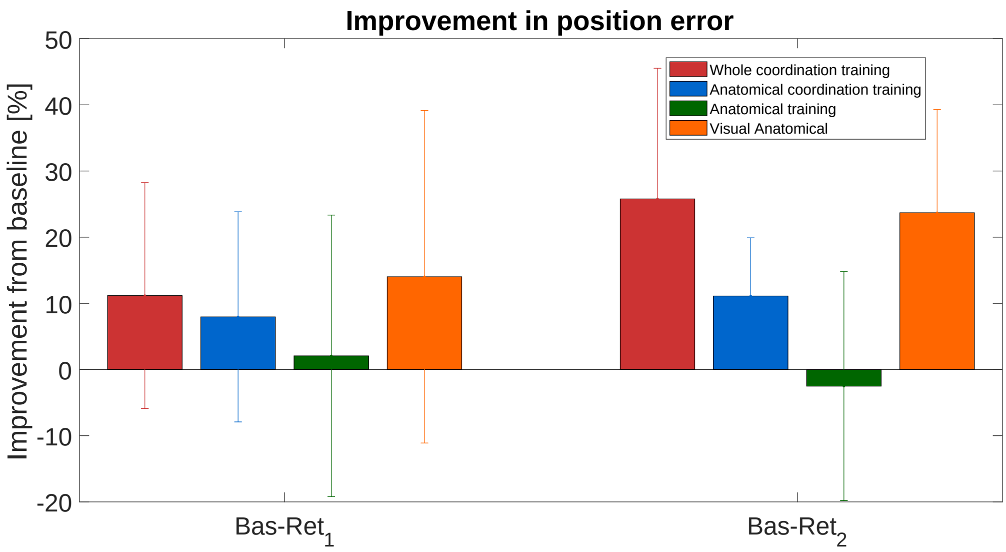
(a) Improvement w.r.t. end of training performance in position coordination as a percentage over end of training skill level.



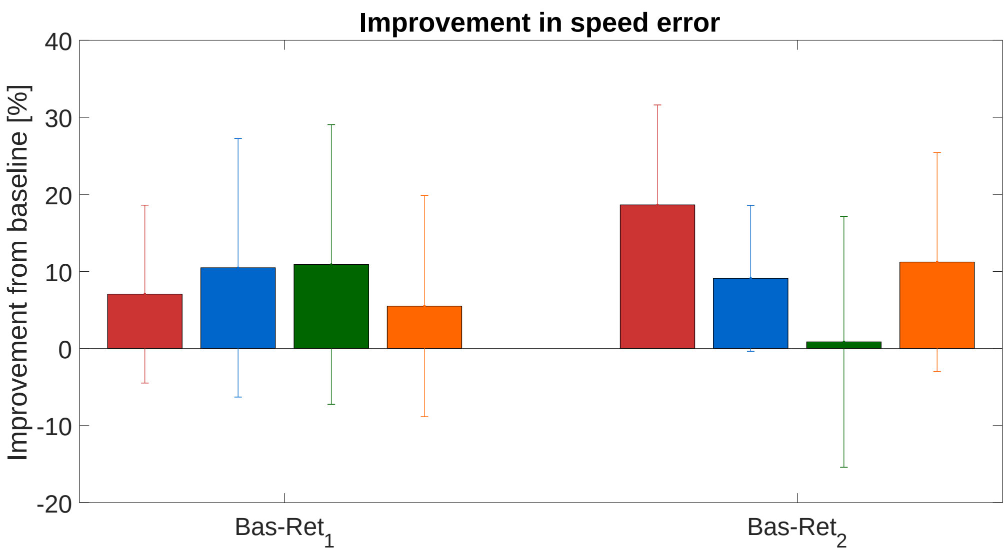
(b) Improvement w.r.t. end of training performance in speed coordination as a percentage over end of training skill level.

Figure A.14: Comparative graph of consolidation of learning level: Pose and dynamic coordination

Transfer of the skills.

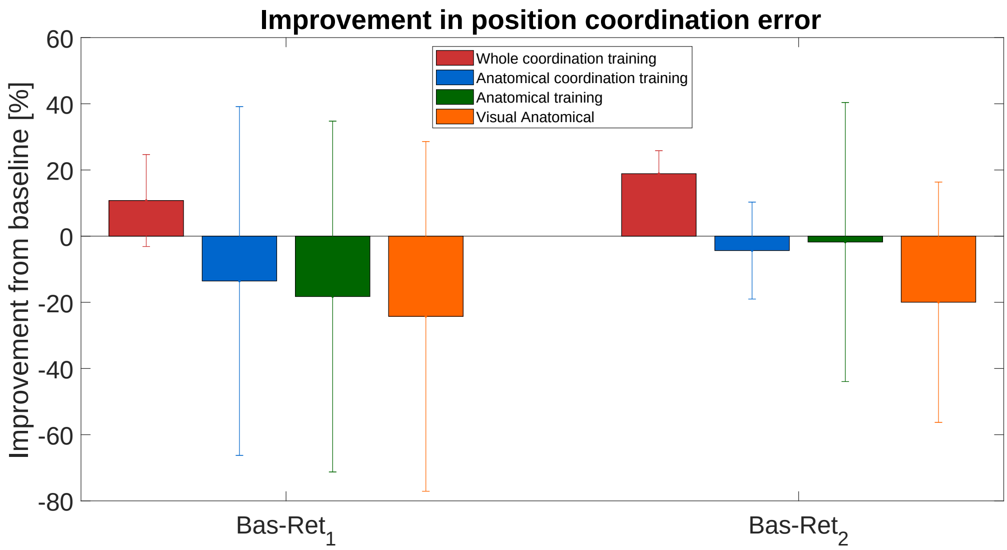


(a) Improvement w.r.t. baseline performance in position (i.e joint angle) tracking as a percentage over baseline skill level.

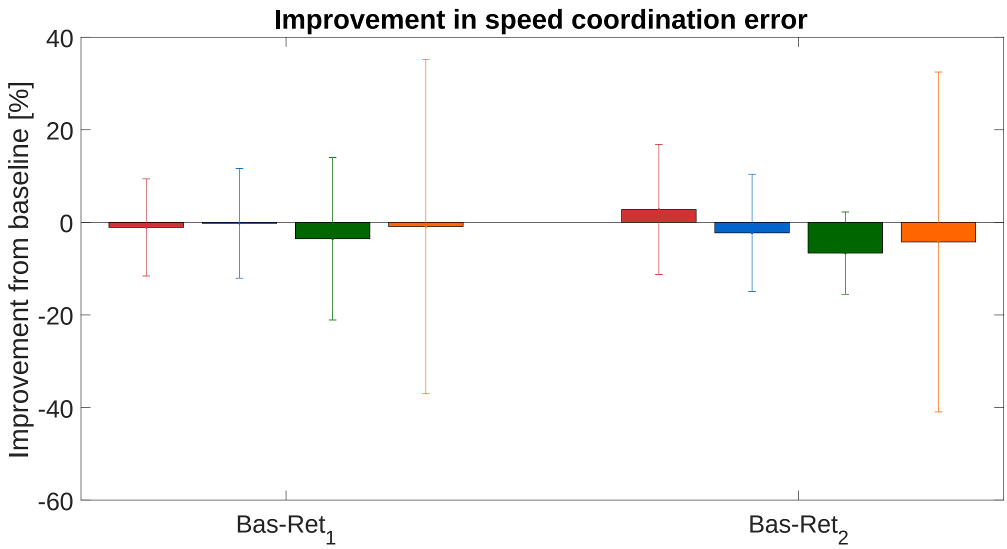


(b) Improvement w.r.t. baseline performance in speed (i.e joint speed) tracking as a percentage over baseline skill level.

Figure A.15: Comparative graph of kinematic parameters for the transfer motion (i.e. forward rugby drilled pass)



(a) Improvement w.r.t. baseline performance in position coordination tracking as a percentage over baseline skill level.



(b) Improvement w.r.t. baseline performance in speed coordination tracking as a percentage over baseline skill level.

Figure A.16: Comparative graph of coordination parameters for the transfer motion (i.e. forward rugby drilled pass)

Statistical testing

Position Error Dataset: Assumption testing

Time Stamp	Group 1	Group 2	Group 3	Group 4
Baseline-Training	D(4)=0.777 p = 0.067	D(3)=0.795 p=0.102	D(4)=0.930 p>0.1	D(3)=0.882 p>0.1
Baseline-Retention 1	D(4)=0.977 p>0.1	D(3)=0.924 p>0.1	D(4)=0.872 p>0.1	D(3)=0.902 p>0.1
Baseline-Retention 2	D(4)=0.847 p>0.1	D(3)=0.988 p>0.1	D(4)=0.874 p>0.1	D(3)=0.760 p=0.021

Table A.2: Position error metric , Normality Tests: Kolmogorov-Smirnov (or Shapiro-Wilk for more conservative evaluation). Non-Normal distribution with p<0.05 in red.

Time Stamp	Statistic
Baseline-Training	F(3,10)=2.019;p=0.175
Baseline-Retention 1	F(3,10)=2.514;p=0.118
Baseline-Retention 2	F(3,10)=9.759;p=0.003

Table A.3: Position error metric, Homogeneity Tests: Levene's test performed on each time stamp measured. Non-Homogeneous with p<0.05 in red.

Speed Error Dataset: Assumption testing

Time Stamp	Group 1	Group 2	Group 3	Group 4
Baseline-Training	D(4)=0.675 p = 0.006	D(3)=0.948 p>0.1	D(4)=0.278 p>0.1	D(3)=0.477 p>0.1
Baseline-Retention 1	D(4)=0.984 p>0.1	D(3)=0.991 p>0.1	D(4)=0.905 p>0.1	D(3)=0.817 p>0.1
Baseline-Retention 2	D(4)=0.950 p>0.1	D(3)=0.767 p=0.039	D(4)=0.976 p>0.1	D(3)=0.815 p=0.021

Table A.4: Speed error metric, Normality Tests: Kolmogorov-Smirnov (or Shapiro-Wilk for more conservative evaluation). Non-Normal distribution with p<0.05 in red.

Time Stamp	Statistic
Baseline-Training	F(3,10)=0.926;p>0.1
Baseline-Retention 1	F(3,10)=0.928;p>0.1
Baseline-Retention 2	F(3,10)=0.932;p>0.1

Table A.5: Speed error metric, Homogeneity Tests: Levene's test performed on each time stamp measured. Non-Homogeneous with p<0.05 in red.

Joint angle coordination Error Dataset: Assumption testing

Time Stamp	Group 1	Group 2	Group 3	Group 4
Baseline-Training	D(4)=0.158 p=0.15	D(3)=0.471 p>0.1	D(4)=0.299 p>0.1	D(3)=0.395 p>0.1
Baseline-Retention 1	D(4)=0.522 p>0.1	D(3)=0.659 p>0.1	D(4)=0.905 p>0.1	D(3)=0.849 p>0.1
Baseline-Retention 2	D(4)=0.708 p>0.1	D(3)=0.185 p=0.15	D(4)=0.601 p>0.1	D(3)=0.447 p=0.021

Table A.6: Pose coordination error metric, Normality Tests: Kolmogorov-Smirnov (or Shapiro-Wilk for more conservative evaluation). Non-Normal distribution with p<0.05 in red. Nearly Non-Normal distribution in orange.

Time Stamp	Statistic
Baseline-Training	F(3,10)=1.844;p=0.203
Baseline-Retention 1	F(3,10)=1.597;p=0.223
Baseline-Retention 2	F(3,10)=1.419;p=0.292

Table A.7: Pose coordination error metric, Homogeneity Tests: Levene's test performed on each time stamp measured. Non-Homogeneous with p<0.05 in red. Nearly Non-homogeneous distribution in orange.

Dynamic coordination Error Dataset: Assumption testing

Time Stamp	Group 1	Group 2	Group 3	Group 4
Baseline-Training	D(4)=0.916 p>0.1	D(3)=0.987 p>0.1	D(4)=0.787 p=0.07	D(3)=0.998 p>0.1
Baseline-Retention 1	D(4)=0.690 p=0.009	D(3)=0.984 p>0.1	D(4)=0.967 p>0.1	D(3)=0.913 p>0.1
Baseline-Retention 2	D(4)=0.865 p>0.1	D(3)=0.997 p>0.1	D(4)=0.933 p>0.1	D(3)=0.960 p>0.1

Table A.8: Speed coordination error metric Normality Tests: Kolmogorov-Smirnov (or Shapiro-Wilk for more conservative evaluation). Non-Normal distribution with p<0.05 in red. Nearly Non-Normal distribution in orange.

Time Stamp	Statistic
Baseline-Training	F(3,10)=0.921;p=0.466
Baseline-Retention 1	F(3,10)=1.328;p=0.540
Baseline-Retention 2	F(3,10)=1.229;p=0.350

Table A.9: Speed coordination error metric Homogeneity Tests: Levene's test performed on each time stamp measured. Non-Homogeneous with p<0.05 in red.

Quality of motion's statistical analysis

Kruskal-Wallis 1-way ANOVA[a]
Consolidation of learning

	Position Retention 1	Position Retention 2	Speed Retention 1	Speed Retention 2	Position Coordination Retention 1	Position Coordination Retention 2	Speed Coordination Retention 1	Speed Coordination Retention 2
Chi-Square	0.794	3.154	1.875	1.478	3.066	11.471	3.507	6.772
df	3	3	3	3	3	3	3	3
Asymp. Sig.	.851	.368	.599	.678	.382	.009	.320	.080

a. Grouping Variable: groupN

Figure A.17: Kruskal Wallis 1-way ANOVA results: Consolitation, factor group. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

Consolidation of skill's analysis

Kruskal-Wallis 1-way ANOVA[a]
Transfer motion

	Position Improv_Ret1	Position Improv_Ret2	Speed Improv_Ret1	Speed Improv_Ret2	Position Coordination Improv_Ret1	Position Coordination Improv_Ret2	Speed Coordination Improv_Ret1	Speed Coordination Improv_Ret2
Chi-Square	1.219	4.848	.195	2.633	.410	1.333	1.776	.519
df	3	3	3	3	3	3	3	3
Asymp. Sig.	.748	.183	.978	.452	.938	.721	.620	.915

a. Grouping Variable: groupN

Figure A.18: Kruskal Wallis 1-way ANOVA results: Transfer motion, factor group. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

Transfer of skill's analysis

Kruskal-Wallis 1-way ANOVA[a]

	Interest s2	Interest s1	Competence s2	Competence s1	Effort s2	Effort s1	Pressure s2	Pressure s1
Chi-Square	3.784	2.407	3.255	3.806	4.734	5.374	.645	1.395
df	3	3	3	3	3	3	3	3
Asymp. Sig.	.286	.492	.354	.283	.192	.146	.886	.707

a. Grouping Variable: groupnumber

Figure A.19: Kruskal Wallis 1-way ANOVA results: IMI, factor group. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

Jonckheere-Terpstra Test[a]

	Interest s2	Interest s1	Competence s2	Competence s1	Effort s2	Effort s1	Pressure s2	Pressure s1
Number of Levels in groupnumber	4	4	4	4	4	4	4	4
N	16	16	16	16	16	16	16	16
Observed J-T Statistic	65.500	60.500	65.500	68.000	66.000	33.000	43.000	46.000
Mean J-T Statistic	48.000	48.000	48.000	48.000	48.000	48.000	48.000	48.000
Std. Deviation of J-T Statistic	10.592	10.550	10.592	10.644	10.557	10.635	10.456	10.500
Std. J-T Statistic	1.652	1.185	1.652	1.879	1.705	-1.410	-.478	-.190
Asymp. Sig. (2-tailed)	.098	.236	.098	.060	.088	.158	.633	.849

a. Grouping Variable: groupnumber

Figure A.20: Jonckheere-Terpstra test results: IMI, factor group. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

Mann-Whitney U-test (Hypothesis 1) [a]

	Effort s2	Effort s1
Mann-Whitney U	2.500	4.000
Wilcoxon W	12.500	14.000
Z	-1.607	-1.169
Asymp. Sig. (2-tailed)	.108 [b]	.243 [b]

a. Grouping Variable: groupnumber

b. 1-tailed: p = 0.052 ; p =0.12

(a) Mann-Whitney U-Test results (Hypothesis 1)

Mann-Whitney U-test (Hypothesis 2) [a]

	Effort s2	Effort s1
Mann-Whitney U	4.500	4.000
Wilcoxon W	14.500	14.000
Z	-1.049	-1.169
Asymp. Sig. (2-tailed)	.294[b]	.243 [b]

a. Grouping Variable: groupnumber

b. 1-tailed: p ≈ 0.15

(b) Mann-Whitney U-Test results (Hypothesis 2)

Figure A.21: Mann-Whitney U-Test results. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

IMI statistical analysis

Kruskal-Wallis U-test[a]

Change in IMI items

	Interest Enjoyment	Perceived Competence	Effort Importance	Pressure Tension
Chi-Square	4.064	5.425	1.417	1.202
df	3	3	3	3
Asymp. Sig.	.255	.143	.702	.753

a. Grouping Variable: groupN

Figure A.22: Kruskal Wallis 1-way ANOVA results: IMI changes, factor group. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

Jonckheere-Terpstra Test[a]

Change in IMI items

	Interest Enjoyment	Perceived Competence	Effort Importance	Pressure Tension
Number of Levels in groupN	4	4	4	4
N	16	16	16	16
Observed J-T Statistic	37.500	23.500	54.500	39.500
Mean J-T Statistic	48.000	48.000	48.000	48.000
Std. Deviation of J-T Statistic	10.601	10.654	10.593	10.680
Std. J-T Statistic	-.990	-2.300	.614	-.796
Asymp. Sig. (2-tailed)	.322	.021	.539	.426

a. Grouping Variable: groupN

Figure A.23: Jonckheere-Terpstra test results: IMI changes, factor group. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

Mann-Whitney U-test (Hypothesis 1)[a]

Change in IMI items

	Interest Enjoyment	Perceived Competence	Effort Importance	Pressure Tension
Mann-Whitney U	6.000	6.000	4.000	6.500
Wilcoxon W	16.000	16.000	14.000	16.500
Z	-.592	-.577	-1.169	-.436
Asymp. Sig. (2-tailed)	.554	.564	.243	.663

a. Grouping Variable: groupN

b. 1-tailed: p≈0.12

(a) Mann-Whitney U-Test results (Hypothesis 1)

Mann-Whitney U-test (Hypothesis 2)[a]

Change in IMI items

	Interest Enjoyment	Perceived Competence	Effort Importance	Pressure Tension
Mann-Whitney U	2.000	1.500	6.500	4.000
Wilcoxon W	12.000	11.500	16.500	14.000
Z	-1.821	-1.888	-.436	-1.155
Asymp. Sig. (2-tailed)[b]	.069	.059	.663	.248

a. Grouping Variable: groupN

b. 1-tailed: p≈0.03 ; p≈0.03; p>0.1 ; p≈0.12.

(b) Mann-Whitney U-Test results (Hypothesis 2)

Figure A.24: Mann-Whitney U-Test results: Hypothesis IMI improvement testing. Level of significance was set $\alpha = 0.05$ for the test with independent variable the group to which subjects were assigned.

IMI time-change's statistical analysis

A.5. Questionnaire

IMI Intrinsic Motivation Inventory

Translated from German(1 – absolutely not , 7 absolutely yes)

- Interest/enjoyment:

1. I really enjoyed this exercise
2. I had a lot of fun with this exercise
3. This exercise bored me
4. This exercise required my attention barely
5. I would describe this exercise as interesting
6. This exercise was nice
7. During this exercise I thought that I am enjoying

- Perceived competence:

8. I think that I was really good in this exercise
9. I think that in comparison to others I executed that exercise better
10. After a short time of training I already felt pretty competent with that exercise
11. I am content with my performance
12. I was really talented in this experiment
13. It was an exercise that I was not really good in

- Effort/Importance:

14. I strained myself a lot
15. I made a big effort in being good in this exercise
16. I made a big effort in execution of this exercise
17. It was important for me to be good in this exercise
18. I didn't put a lot of energy in this game

- Pressure/Tension:

19. I wasn't nervous during the training
20. I was really tense during the training
21. I was really relaxed during the training
22. I was anxious during the training
23. I felt to be under pressure during the training

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