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Un'indagine cinematica sul ruolo dell'osservazione dell'azione nell'apprendimento motorio

An investigation of action observation-based motor learning through kinematics analysis

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ABSTRACT

It has been demonstrated that observing actions plays a fundamental role in learning new motor skills. On this knowledge, the Action Observation Treatment (or Training) (AOT) was defined as alternating the observation and the execution of actions. In this thesis, after a literature review on the effectiveness of AOT in rehabilitation and learning new motor skills, I present the methodological framework and preliminary results of a study investigating the role of AOT in learning motor sequences typical of martial arts.

The main purpose of this study is to test the greater effectiveness of AOT compared to MP in motor learning. In addition, a second objective is to verify the potential of AOT in the generalization of learning, that is, the ability to acquire new information more easily in a situation where practice takes place in a scope that is compatible with that of the previously learned information, and that has consistency with the acquired knowledge.

With these objectives, the performance of motor learning by AOT is compared with those achieved during learning with motor practice (MP). Twelve healthy subjects who were naïve in dance and martial arts were recruited to participate in seven full-body kinematics sessions conducted over four weeks. They had to observe an expert model practice sequence and subsequently repeat them as accurately as possible. The training consisted of six sessions carried out over two weeks, and then the follow-up was conducted during the fourth week. Each subject during each session underwent learning of four motor sequences, two by the AOT method and two by the MP method. In the follow-up session, they were asked to reproduce two untrained motor sequences with AOT to assess generalization.

To compare the effectiveness of the two methods, I calculated the Learning Rate, Decay, and Consolidation Rate. I verify the generalization of learning by comparing the average of correlations related to the executions of the untrained sequences on the seventh day with that of the sequences during the first training day.

In this thesis, the results of three participants are reported, as recruitment and respective analyses are still in progress. Learning after training was observed in both conditions, but Action Observation Training revealed higher learning than the MP method. The learning rate is greater in the AOT condition (0.3267) than in the MP (0.3000) condition during the two-week training. The decay value from the end of training to follow-up in the AOT condition is lower (0.0133) than in the MP condition (0.1333). Moreover, the consolidation rate is higher for the AOT method (95.92%) than for the MP method (55.56%). Furthermore, a generalization of learning of AOT occurred as the performance of the untrained sequences executed during the follow-up was higher (0.2477) than the correlation values of the sequences performed during the first session (0.1400).

These preliminary results demonstrate AOT's role in acquiring new motor skills by showing greater effectiveness and consolidation over time. Furthermore, a generalization effect is observed, i.e., an ability to learn new stimuli that belong to the same motor repertoire as previously acquired stimuli.

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1. INTRODUCTION

Observing others performing any action is part of our daily life and helps us understand the space and environment in which we live. We learn motor behavior by observing and imitating certain actions or sequences performed by skilled people in work, sports, and even our daily lives.

Canadian psychologist Albert Bandura is the father of the social learning theory. According to this theory, individuals' learning does not come solely through direct experience but also through indirect stimulations developed by observing others.

Bandura coined the term “Modelling,” which is a learning process that is triggered when the observer's behavior is changed according to the behavior of another individual who then serves as a model. Bandura's theories link to the discovery of the mirror system (MNS), activated when we observe and perform an action. Mirror neurons appear to be the background for a motor resonance mechanism, whereby "we understand actions when we map the visual representation of the observed action onto our motor representation of the same action" (Rizzolatti et al. 2001). These findings led to the idea that the activation of mirror neurons was at the basis of learning by imitation, concluding that the same parietal-frontal areas remain active during observation and during the subsequent execution of the same action (Buccino et al. 2004). Based on these findings, we investigate the effectiveness of a new learning method, Action Observation Training, which benefits from both the effects of the observed action and execution.

1.1. The role of Action Observation in Cognition

Observing action is essential in daily life as it improves our motor skills. Through observing an action performed by others, we can understand the meaning of the action and learn and imitate it. In addition, we can correct our previous performance if it was inadequate, intending to improve it.

During the observation of an action, a neural network called the "Action Observation Network" is activated in the beholder. This network includes several (Cross et al. 2009), such as the inferior frontal gyrus (IFG, BA44/45), dorsal and ventral premotor cortex (dPMC, vPMC), inferior parietal lobule (IPL), superior parietal lobule (SPL), inferior parietal sulcus (IPS), the primary motor cortex (M1) and primary somatosensory cortex (S1), the posterior medial temporal gyrus (pMTG), the fusiform face/body area (FFA/FBA) and the visual area V5 (Caspers et al. 2010). The frontal-parietal regions are involved in action planning (Gallese et al. 1996; Buccino et al. 2001), while the superior temporal sulcus and occipital-temporal visual areas are involved in perceptual analysis (Carr, Iacoboni, Dubeau, Mazziotta and Renzi, 2003).

Underlying this network are mirror neurons, which are visuomotor neurons discovered in the ventral premotor cortex of the macaque (F5), and later also found in the parietal lobe (PF) and inferior rostral (PFG). What has been shown is that these neurons are activated both when we watch others performing an action and when we perform it ourselves (Di Pellegrino et al. 1992; Gallese et al. 1996; Rizzolatti et al. 2001; Fogassi et al. 2005). It has been demonstrated that this mechanism underlies understanding the meaning and intentions of observed actions such as grasping, pushing, and dragging activating mirror neurons (Gallese et al., 1996; Rizzolatti et al., 1996). Later studies showed that even complex actions such as climbing (Abdollahi et al., 2013) and using tools (Caruana et al., 2017) led to the activation of this particular class of neurons. What happens is that sensory information is transformed into motor representations. Surprisingly, it happens not only in the parietal and motor cortex but also in the insula (Wicker et al. 2003) and cingulate cortex (Caruana et al. 2017). This common activation of partly overlapping neural networks suggests a common neural code for one's own and others' actions (Rizzolatti and Craighero, 2004), leading to the idea that there must be a motor knowledge of the action, which would be crucial for the observer's understanding. The discovery of mirror neurons in the monkey suggested that a similar system might also exist in humans. Studies (Fadiga et al. 1995) have shown that in humans, unlike monkeys, activation is present even during purposeless actions.

Further confirmation of the importance of motor knowledge for understanding the actions of others was given by Calvo-Merino et al. (2005). The study, conducted using fMRI, showed videos of capoeira dance and ballet dance to three groups: capoeira dancers, ballet dancers, and subjects naïve in the two domains. The results showed greater activation of the mirror regions of the premotor cortex when dancers watched videos of subjects practicing their sport, while control subjects showed less activation. Thus, observing an action that is part of the observer's motor repertoire and experience leads to greater activation of mirror regions and, therefore, the action observation network (AON). It was also found that activation of frontal and parietal regions was greater for motor familiarity than for visual familiarity. This was demonstrated by evaluating the activations in men and women to test whether the increase in mirror regions was due to observation of the partner's steps or whether it was related to one's own. The results confirmed the latter hypothesis. The study demonstrates the specificity of the action-observation network in that experienced dancers exhibit different activations based on experiences differentiated by sex or dance type (Calvo-Merino et al., 2006). A further study replicated the results of the previous one by investigating differences in activation (fMRI) between experienced and non-experienced archers. Results showed greater activation of AON/mirror e networks in the hemisphere corresponding to the counterpart used, so activation was attributed to the greater familiarity elicited by the stimulus (Kim et al., 2011).

According to Jeannerod, an important function of mirror neurons would be to create, through observation of an act, an "internal motor representation" that would support learning by imitation. Iacoboni and coworkers (1999) argue that imitation occurs by transforming sensory information into motor activity. In an experiment in which participants were asked to imitate finger movements they had previously observed, the authors demonstrated increased activation of the opercular region of the left inferior frontal cortex and the more rostral part of the right superior parietal lobule. At the same time, there was less activation in the case of different finger movements or symbolic signs.

Another significant contribution to learning by imitation was made by Buccino and coworkers (2004), who conducted a study using functional magnetic resonance imaging. The experiment consisted of 4 phases: observing the guitarist while playing chords; imagining the observed actions; performing the observed chords; and resting. The authors report that the frontal-parietal network, particularly the inferior parietal lobule and inferior frontal gyrus, is active during all phases of learning.

1.1.1. Action Observation, Motor Imagery, and Movement Execution

Buccino and coworkers (2004) show that observing, imagining, and performing an action leads to a common activation of areas. Through analysis of hundreds of studies (Hardwick et al. 2018), they concluded that premotor, parietal, and somatosensory activation is always involved during the various phases. The most widely accepted hypothesis is that it would be of little use to have three different networks for the three tasks of action observation, motor imagination, and movement execution, as they are similar (Hétu et al., 2013). This could be useful in motor skill acquisition and, more importantly, in clinical settings. For example, an animal study shows that action execution in the acute phase after stroke leads to general improvement (Zeiler and Krakauer, 2013). Therefore, during the motor imagery, there is an overlap with the cerebral circuits regulating action execution. This finding could be used for training purposes in the clinical setting because, generally, patients with brain damage, like in stroke, cannot engage in physical activity in the immediate aftermath.

Jeannerod (2006) defines motor imagery as "an internal motor representation lacking only the final execution of the action." Various studies have shown that training with motor imagery allows for greater muscle strength without hypertrophy (Lebon et al.,2010; Yue and Cole, 1992). In addition, combining physical training with motor imagination led to more effective learning than physical execution alone (Allami et al. 2008). Imagining touching an object induces increased corticospinal excitability and parietal-frontal regions, demonstrating that appropriate sensory cues can provide better resolution than motor imagination (Mizuguchi et al., 2009, 2011, 2012b, 2015).

During motor imagery, the SMA, IPL, and SPL are activated (Decety et al., 1994; Mizuguchi et al., 2013a, 2014a, b). According to the studies reviewed by Hardwick and colleagues (2018), there is always activation of the dorsolateral prefrontal cortex and frontal thalamus, probably due to working memory or a movement inhibition task performed by the dorsolateral prefrontal cortex. Motor Imagery and Action Observation activate the parietal and premotor areas. In contrast, motor imagery and movement execution activate, in addition, other regions such as the putamen, cerebellum, and media-cingulate cortex.

In the case of the media-cingulate cortex, motor imagery activated a more anterior area that deals with a more cognitive aspect of movement (Hoffstaedter et al.,2014), while execution activated a posterior area related to basic functions of movement (Picard and Strick, 1996; Procyk et al., 2016).

Motor imagery and action execution activate the bilateral putamen, part of the basal ganglia, and is involved in automatic movements (Voon et al., 2015), speed, and extension of movements (Turner et al., 2003). Being affected by Parkinson's disease, which is part of the basal ganglia disorders, results in the slow movement (Dickson, 2018). It has been shown that slowness of movements also affects imagined movements (Helmich et al. 2007; Heremans et al. 2011); from this, we can guess why they are not activated by observation of action, which does not imply speed of movements.

The areas activated during action observation are the premotor and parietal regions. There appears to be occipital activation given by the observation of action. There is also extrastriate visual activation given by observing body parts and movement (Downing et al., 2001; Ferri et al., 2013; Urgesi et al., 2007). During action observation, compared to motor imagery, there is greater activation of the inferior frontal gyrus, ventral premotor cortex, and inferior/superior parietal cortex. The ventral premotor cortex corresponds to the F5 area of the macaque where mirror neurons are present (di Pellegrino et al. 1992; Rizzolatti et al. 1996), so these activated regions are thought to be important for the action observation network (Caspers et al. 2010).

During Action Execution tasks, the sensorimotor and premotor cortices are active. In addition, there are subcortical activations of the putamen and thalamus, and somatotopic activations, thus containing motor maps of the primary motor cortex and cerebellum (Buckner et al. 2011; Schlerf et al. 2010).

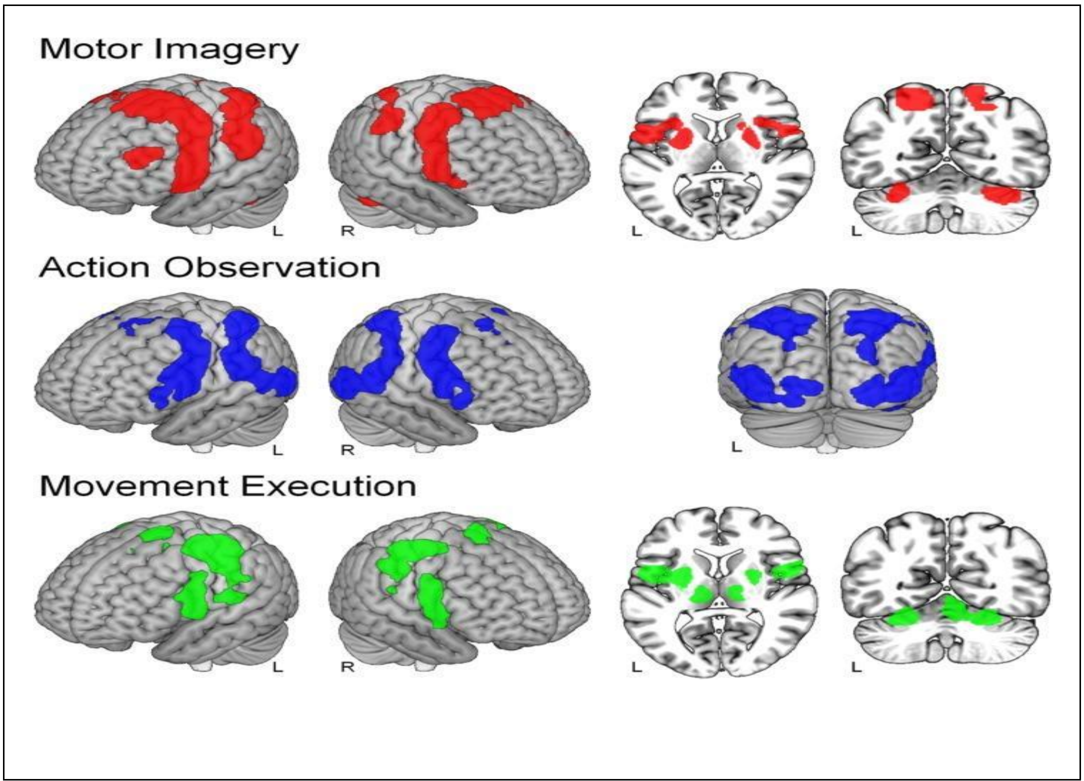


Fig. 1 - Neural activation during motor imagery, action observation, and movement execution (From Hardwick et al. 2018).

1.2. From the Treatment to Training

Action Observation Treatment is based on several stages: observation, motor imagination, and execution. During observation of an action, there is already activation of premotor, parietal, and somatosensory areas; these activations persist during motor imagery and facilitate subsequent execution. AOT consists of alternating action observation and execution to benefit from observational learning and motor practice. Action observation (Stefan et al., 2005; Celnik et al., 2008) leads to changes in neuroplasticity that have long-term consequences in cortico-motor excitability. Behavioral efficacy resulting from AOT causes an enhancement of cortical and subcortical connections in the premotor and parietal. Various hypotheses have been made about how this happens: it could increase M1 excitability, or projections starting from the premotor cortex could lead to better execution at the behavioral level (Rizzolatti et al., 2014). Another hypothesis is that corticospinal pathways are formed due to the activation of M1 neurons (Vigneswaran et al., 2013).

Celnik and coworkers (2008) have used Action Observation Treatment in both healthy individuals and stroke patients, demonstrating that even just observing, without performing, the action can lead to cortical changes in M1, functional reorganization, and thus neuroplasticity, which allows for improved motor skills (Nudo et al. 1996; Traversa et al.,1997; Chieffo et al., 2013, 2016,

1.2.1. AOT in rehabilitation

Rehabilitation can be considered a learning process in which skills impaired by a musculoskeletal or cortical injury are relearned. Practicing an exercise with a particular body part causes it to expand its representation at the cortical level. AOT has shown benefits in this area by going on to promote functional recovery in disorders such as stroke, Parkinson's disease, infant cerebral palsy, and orthopedic recovery after surgery (Rizzolatti et al., 2021)

AOT was used for the first time with patients who had undergone orthopedic surgery; the treatment lasted about three weeks (6 days a week), during which a specific group of patients, the experimental group, were shown videos with a particular content of motor. In contrast, the control group observed nonspecific videos. The study results show that, at discharge, almost all the subjects in the experimental group were using only one crutch, while more than 20 percent of the subjects in the control group were still using two crutches (Bellelli et al. 2010).

Another study confirms the effectiveness of Action Observation Treatment was done by Villafañe et al. (2017) on patients who had undergone total hip arthroplasty. One group observed videos with actions (AOT), while the control group observed videos without motor content. The patients who underwent AOT felt better than the control patients, and they could flex and extend their knees more.

AOT could be combined with classical physical rehabilitation to prevent the patient from worsening his condition since he cannot move due to the injury. Therefore, through action observation and motor imagery, the patient can recover and reconsolidate correct motor programs and counteract maladaptive cortical changes (Bassolino et al., 2014; Zink and Philip, 2020).

Application of Action Observation training treatment improved the recovery of patients with upper limb motor deficits due to stroke. A study by Ertelt et al. (2007) shows that there can be an increase in the activity of mirror regions (ventral premotor cortex, supplementary motor area, supramarginal gyrus) by observing actions of daily living. The patients involved underwent AOT treatment for four weeks, resulting in improved motor activities of the deficit limbs. In addition, increased excitability of the primary motor cortex in the area corresponding to the muscles of the action being observed was observed by transcranial magnetic stimulation (TMS) (Celnik et al. 2008).

AOT also showed benefits in the case of patients with aphasia, who first had to observe and perform a given action and then name it or observe and name it. What turns out is that in both conditions, patients had presented an improvement in the production of verbs describing actions; this persisted even two months after the end of treatment (Bonifazi et al. 2013; Marangolo et al. 2012).

In recent decades, the effectiveness of AOT application has also been confirmed in children with infantile cerebral palsy. Buccino et al. (2012) conducted a study in which two groups of children with cerebral palsy; the control group had to observe videos without motor content, and the experimental group had to observe videos of actions performed with the hand. The results indicated an improvement in hand actions in the experimental group compared with the control group.

Children with CP who undergo Action Observation Training treatments show an improvement in goal-directed actions over kinematics itself (Sgandurra et al.2013). The activation of the mirror network may give this, thus the frontal-parietal regions involved in encoding hand-grasping actions, as shown in a neuroimaging study (Buccino et al. 2018), in which this activation was found to be higher after the application of AOT.

Action observation sessions also proved helpful in subjects with neurodegenerative diseases. Applications of AOT meant that there was a slowing of skill decline due to the effects of the disease. Sixty-four subjects with Parkinson's disease (Pelosin et al. 2018) showed improvement in motor skills four weeks after the end of the rehabilitation session, during which they observed actions. Then they practiced motor workouts, while the control group, which practiced workouts but watched videos of landscapes, showed no improvement after four weeks. According to the results of Agosta et al. (2017), obtained through fMRI, subjects undergoing AOT have greater activation of frontoparietal regions, which was found to be predictive of the subsequent improvement in subsequent weeks.

1.2.2. AOT in motor learning

While AOT has yielded important results in improving functional recovery of movement in patients with motor system diseases by developing therapeutic and rehabilitative tools, it was evaluated that AOT could also be applied to acquire and develop new procedures in sports.

For example, professional athletes are prone to cruciate ligament rupture, which can cause serious damage to their careers. So, in addition to common warm-up practices, they can be subjected to the AOT procedure: athletes observe videos of optimal performance to perform, as accurately as possible, the correct movements (Benjaminse and Otten, 2011).

Gokeler et al. (2013) proposed a procedure, the "Video Overlay," in which the athletes' body is superimposed with that of a model during the performance of the exercise; then, the athletes view the video and try to decrease the error by superimposing their own body with that of the model as much as possible.

A study (Mattar and Gribble, 2005) was conducted to demonstrate the effectiveness of AOT procedures in motor learning as well; observing a subject learning a particular motor act causes the observer, in turn, to learn the motor act more efficiently. Two groups of people were involved in the study, with the first group observing a subject who performs performances that gradually improve and the second group observing a subject who serves performances without any improvement. The second part of the study involved performing the observed action, with the first group demonstrating better performance than the second group. Observing an expert perform a motor act using a particular strategy, such as observing an expert mountaineer perform a climb, makes one more likely to repeat it as a result of motor system activation for that particular action (Boschker et al. 2002).

Another study shows that direct observation of performance, then receiving verbal instructions, promotes learning. In the study conducted by Horn et al. (2007), they recruited subjects who were baseball beginners, and during the experiment, they had to throw the ball as fast as possible toward a target. The results showed that after watching the video, the subjects imitated the observed movement.

AOT has also shown benefits in the field of surgery, which requires learning fine and accurate motor control. A demonstration of the effectiveness of observation is given by Custers et al. (1999). The study shows that students who watched videos of operations performed better than control subjects. In addition, observing errors also seems likely to lead to better performance; this was investigated by LeBel et al. (2018) through a study in which some subjects observed an expert or an untrained person practicing a surgical task. The results showed improved performance in both groups, while after one week, the group that had observed the untrained showed better performance than the expert group. This suggests that observing errors may help to remember to correct them so that they are not made later (Harris et al., 2018).

Gonzales-Rosa and coworkers also confirm the benefits of observational learning with a study whereby different performances are compared, and the effectiveness of learning after observing or imagining a four-limb hand-foot coordination movement is tested. Three groups were involved: the first AO (action observation) observed videos of the task, the second MI (motor imagery) group imagined the task, and the third was a control group that performed calculations. The subjects then had to perform the movement while the error of the performance was measured and compared with the correct performance. Analyzing the EEG collected during the training phase, it was found that the AO group had greater desynchronization of the alpha bands (8-12 Hz) in the frontocentral, and bilateral parietal regions compared with the MI and C groups. In contrast, during the performance of the AO group, there was greater desynchronization of the beta bands (14-30 Hz). The latter was found to be a predictor of the measured error, which is lower during greater desynchronization, therefore, predicts better performance.

The study shows that action observation, which leads to greater cortical activation, promotes more efficient motor learning than motor imagination. An important factor to note is that suppression of the alpha rhythm, called "mu," accounts for the modulation of mirror neurons in the prefrontal area; this suppression is present both when performing the movement and when observing or imagining the movement itself (Pineda, 2005).

1.2.3. AOT-induced neuronal changes

Observing a new movement and tending to execute it showed satisfactory behavioral results, which are reflected in brain changes. Indeed, acquiring new skills leads to neural reorganization (Draganski et al. 2004), during which activity decreases or increases according to the stages of learning. What happens is that observing a novel movement, and tending to execute it as well, induces an increase in AON activity. The early stage of learning, called the "fast" stage, induces a decrease in activity (Liew et al.,2013), probably because motor performance improves rapidly. In contrast, the next stage of learning, termed "slow," leads to increased activity of sensorimotor regions because of cortical expansion in the areas representing that body part (Karni et al.,1995). After one reaches a level of expertise and continues the practice over time, the cortical expansion stabilizes and gradually decreases. In fact, there is less activation compared to non-experts during a performance (Nakata et al.,2010). Whereas the opposite happens during observation; thus, AON activity is greater in experts than in novices, the probable cause being understanding of the action (Calvo-Merino et al.2006).

Various studies have investigated changes in the AON network during the acquisition of new movement sequences in both experienced (Cross et al., 2006) and naïve subjects (Cross et al., 2009; Mizuguchi and Kanouse., 2017), demonstrating increased activations after learning. In contrast, other authors have presented opposite results showing decreased activity after learning (Vogt et al., 2007; Babiloni et al., 2009, 2010).

Cross et al. (2006) conducted a study during which experienced dancers had to memorize new dance movements over five weeks. In the study, fMRI was used to assess brain activity as the subjects observed and imagined different dance sequences; some of these sequences were also practiced while others were not. The areas activated during the observation and execution of the dance sequences were the inferior parietal lobule (IPL) and ventral premotor areas (vPMC), the activation of which depended on the participant's experience and the rating they gave to their ability to execute the sequences, which was higher for the practiced sequences. The results showed that there is tuning and increased activation of the AON; this shows a simulation of action even in the case of short-term learning (Cross et al. 2006).

The follow-up study (Cross et al. 2009) recruits, compared with the previous study, subjects who were not experts in the field of dance and who had to passively observe videos of dance sequences or practice other sequences for five days. The purpose of the study is to compare differences involving neural and performance activations between learning by observation alone and learning also accompanied by physical practice. Subjects underwent fMRI on the first and last day. The results show lower premotor and parietal activation during observation of passively practiced or observed sequences, which decreases in the case of non-practiced sequences. The results show that passive observation or practice of certain movements leads to activation of AON, unlike previous studies (Calvo-Merino et al.2006), according to which there is strong activation during physical practice while passive observation alone does not lead to motor experience.

Further confirmation was provided by Mizuguchi and Kanouse (2017), who went to investigate through a longitudinal study with fMRI how the activity of the AON changes during the phases of learning a complex movement. The authors recruited naïve subjects to acquire a "kip" movement over two months of training. The subjects were subjected to fMRI at the beginning and end of the training sessions (for simplicity, activations during action observation were assessed). What emerges is that before training, only V5 is active, while after movement acquisition, the bilateral V5 area, right PMv, and SMA are also active; these results confirm an increase in AON activity.

Other studies have, however, reported how experiences of observing action could lead to decreased activity in AON areas. One study (Vogt et al., 2007) showed that this network's modulation also depends on one's intention when observing a particular action; observing unpracticed guitar chords led to stronger activation than observing already imitated chords, thus, the intention to imitate induced a decrease. Another cause of this decrease could be the familiarity and knowledge of the practiced action.

Using EEG, and thanks to the temporal resolution of this technique, it was possible to investigate the changes induced by learning through observation. Action experiences with unfamiliar drawings resulted in greater mu rhythm desynchronization during observation of the previously practiced drawing action (Marshall et al., 2009). Furthermore, the greater the accuracy of imitation, the greater the desynchronization upon observation (Casile and Giese, 2006). There are also conflicting studies (Babiloni et al., 2009, 2010) showing less desynchronization in experienced subjects when observing actions from their motor repertoire compared to less experienced subjects. Moreover, desynchronization was also lower for expert observers who judged accurately compared to less accurate observers. According to the authors, the lower desynchronization is given, as it happens during execution, by the higher neural efficiency.

1.2.4. AOT-induced kinematics change

Motor learning leads to changes in one's repertoire, allowing one to acquire new skills through continuous interactions with the environment, which stimulate the motor system (Wolpert et al. 2001; Krakauer et al. 2019; Gatti et al. 2013). Physical training is characterized by continuous repetition of trial and error leading to subsequent correct practice (Coker, 2004), which is manifested by a progressive decrease in errors, reduced movement duration, and increased precision and fluidity during execution (Dugas and Marteniuk, 1989). As discussed in the previous paragraphs, in addition to motor execution, observation also appears to be an effective tool that could promote motor learning. Action Observation Training (AOT), which includes and alternates between execution and observation, should give a greater advantage for learning new motor skills; this technique should therefore lead to a change in kinematics during training.

Gatti and colleagues (2013) studied the role of motor imagination and action observation in motor learning by investigating kinematics during the acquisition of a complex motor task. The task consisted of bringing the right hand and foot in the same angular direction (in-phase movement) and simultaneously bringing the left hand and foot in the opposite direction (antiphase movement). Kinematics data were recorded through an optoelectrical system consisting of six cameras. Twelve passive markers were placed bilaterally to sample the kinematics of the wrist (in the lateral condyle of the humerus, the styloid ulnae, and the head of the fifth metacarpal) and the ankle (in the head of the fibula, the lateral malleolus, and the head of the fifth metatarsal). Various kinematic parameters, including the direction of the four extremities of the body segments, the amplitude of the movement, and the delay of the body segments, were considered to evaluate the correct execution of the motor act. The results showed that observing the action is a better strategy than visual imagination for learning motor tasks. This can be explained by the fact that looking at the action is more effective for applying it; in practice, it is easier to learn if you observe than if you learn based on imagination alone.

The study conducted by Al-Abood et al. (2001) analyzed the kinematics of three groups of subjects to compare learning to throw darts through either verbal instructions or visual demonstrations. The first group observed an experienced model and practiced throwing alternately, the second group received verbal instructions related to the model's movement pattern, and the third group was the control. Kinematic data were recorded through a motion system that consisted of two cameras detecting different markers. The markers were placed at three points on the arm used during the performance, specifically at the shoulder, elbow, and wrist. The kinematics results showed that visually observing a pattern, as in the first group condition, leads observers to acquire the coordination pattern shown visually. Instead, receiving verbal instructions or the absence of instructions led the other two groups to reproduce a completely different launch pattern from the model's. In addition, the first group demonstrated an acceleration of the learning process and, thus, a rapid convergence to the movement pattern of the model.

And colleagues (2014) demonstrated how Action Observation practice, compared to traditional practice, is also effective in resistance training, specifically in weightlifting. The authors evaluated the improvement of kinematics and kinetics in inexperienced subjects who had to learn an exercise (power clean) through action observation (AO) or traditional technique (TC). Subjects in the traditional group received verbal feedback on the physical practice, while subjects in the action observation group watched videos of the movement in addition to verbal instruction. Kinematic performance was assessed through video recordings of subjects with central joint markings applied and was asked to minimize the possibility of marker movement and wear adhesive and compression tops. In addition, a weightlifting analyzer that was attached to the barbell was used. Participants performed 12 sessions over four weeks. Video recordings were analyzed through software that used joint angles and distances (torso angle, hip angle, knee angle, ankle angle, shoulder angle, and shoulder-to-barbell distance) as comparison measures to assess differences between the AO and the control groups, and the expert. The authors report that the AO group improved technique and power clean performance faster than the TC group.

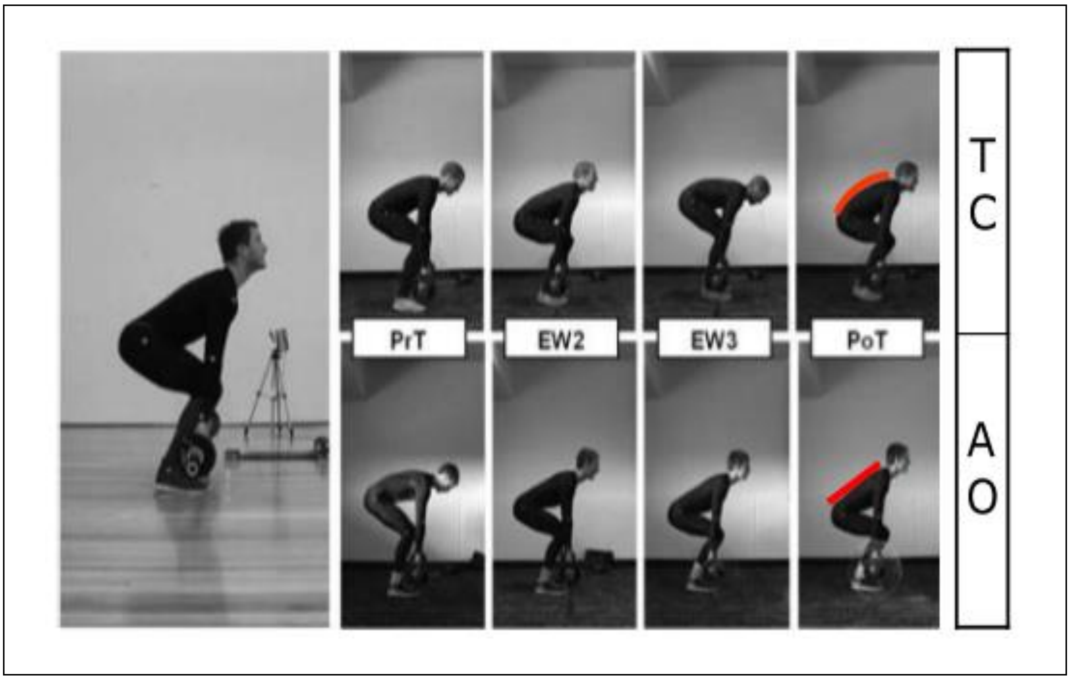


Fig. 2 Comparison between the two groups and the expert model in the execution of the take-off (Sakadjian et al. 2014).

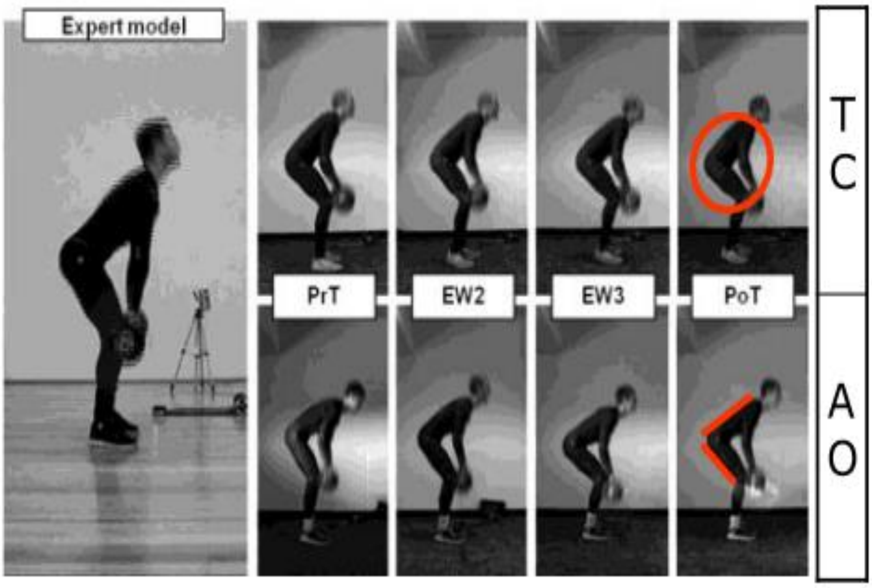


Fig. 3 - Comparison between the two groups and the expert model in the execution of momentum (Sakadjian et al. 2014)

It is possible to conclude by stating, given the previous studies, that viewing a pattern is more effective, compared to traditional practice by execution, for learning new skills because it leads the observer to change their pattern of behavior and motor coordination like that of the observed pattern. Therefore, Action Observation Training (AOT), which alternates each execution with a viewing, allows the observer to have visual information after each rehearsal. This allows continuous corrections in the various phases until the correct technique is achieved, more quickly than other learning techniques.

1.3. Generalization of learning

According to schema theory (Schmidt, 1975), learned movements create generalized motor programs, which are then recalled in memory and allow for facilitating the motor performance of new tasks; what takes place is a transfer of information. According to theory, when going to perform a previously learned movement, recall memory is called into play, and recognition memory is used to verify its correctness. In addition, according to the author acquiring variable practice leads to a transfer of information and, thus, to greater generalization.

Based on these assumptions, King and coworkers (2019) investigated the role of generalization after acquiring motor sequences. The experiment is carried out two days in a row. During the first day, they learn sequences that are to be performed on the computer keyboard based on the information shown on the screen. During the second day, they repeat the same sequences acquired and are subjected to learning new ones. The reported results show that the new sequences presented on the second day are learned more easily than the sequences presented on the first day. This is explained by the fact that the domain in which they are learned is compatible, and the information is consistent with each other. Furthermore, the execution of the previous information does not interfere with the execution of the new information; this suggests that the information can coexist and is incorporated into the already established memory.

1.4. The experimental study

The purpose of this study is:

1) To evaluate participants' learning during Action Observation Training (AOT) by verifying the effectiveness of AOT in acquiring new motor sequences compared to motor practice (MP).

2) To investigate the potential of AOT in generalizing learning by subjecting participants, during the seventh session, to new stimuli using the AOT learning method.

To achieve these goals, twelve participants had seven sessions conducted over a four-week period in which each participant was subjected to two learning methods: Action Observation Training (AOT) and Motor Practice (MP). The full-body kinematics of each subject were recorded using inertial sensors and then compared with that of the expert model shown during the observation. Electroencephalographic (EEG) recordings during the first and last session of training, and follow-up, were performed during rest and while observing the motor sequence to learn to investigate the power of functional connectivity in learning prediction.

My thesis will focus on the kinematic analysis as I contributed to the first part of the project, assisted in the paradigm definition, recruited participants, and contributed to the recordings of 12 subjects. In the process, I contributed to the analysis of kinematic data.

2. MATERIALS AND METHODS

2.1. Participants

Twelve subjects naïve in dance and martial arts were recruited for the experiment (age= 25,3, SD = 4,5; seven females e five males). According to the Edinburgh Handedness Inventory (Oldfield, 1971), the participants are right-handed. Also, they do not have physical, neurological, or psychiatric disorders.

At the time of recruitment, subjects were sent an online questionnaire on their degree of familiarity with martial arts and dance. The questions were about sports they practiced: first, they were asked whether they practiced martial arts or dance, and in the case of a yes, age and duration; then, what other sports they practiced and how often. We excluded subjects who practiced dance or martial arts for more than two years, while subjects with no or little experience in these two sports were recruited.

The local ethics committee approved the study (Ethics Committee of the Northern Emilia Vast Area, No. 10084, 12.03.2018) according to the principles expressed in the Declaration of Helsinki. Participants provided written informed consent and received payment.

2.2. Questionnaires

Before the experimental procedure, participants were subjected to the questionnaire to assess the degree of vividness of motor imagination (VMIQ-2, Roberts et al. 2008). The test consists of imagining performing twelve actions with eyes closed according to three different perspectives: looking at self from the outside (external visual imagination), looking at self from the inside (internal visual imagination), and feeling the sensation of movement during the same (kinaesthetic imagination). Then subjects were asked to rate the degree of vividness on a scale: clear and vivid (as in normal vision or sensation of the movement); clear and reasonably vivid;

moderately clear and vivid; vague and indistinct; no imagery, only awareness of being thinking about the movement.

In addition, visuospatial working memory was assessed with a digital version (PEBL Mueller and Piper, 2014) of the Corsi Block Span (Corsi, 1972; Kessels et al., 2000); the test aims to reach subjects' ability to reproduce sequences of blocks; the length of the blocks increases when the Corsi test proceeds. The test stops when a subject cannot reproduce a sequence after two trials. Subjects were subjected to these two tests because learning can be influenced by motor and visuospatial imagery skills.

2.3. Stimuli

The stimuli consisted of six videos depicting seven motor acts taken from martial arts movements. So, there are 42 motor acts in all; it is important to note that they differ. We checked them individually, and the correlation between each motor act and to other was low. Before the start of the main experiment, these motor acts are designed by a martial art expert precisely. Then, he performed these different sequences, and the videos were recorded from a frontal perspective.

Before the training session, participants wear the MVN Link Lycra suit, which covers the entire body and is sided with gloves and a headband. Based on the subject's height and weight, the size (S to 4XL-six sizes in all) is tentatively chosen, and after it is put on, the appropriate comfort and fit are checked. The suit keeps the inertial sensors in place on various body parts and makes the participant comfortable.

Fig. 4 - MVN Link Lycra Suit (a) with headband (b) and glove (c); (from MVN User Manual).

After size is chosen, all body measurements are taken and placed within the participant's profile so that MVN Analyze/ Animate can estimate the length of the various body parts. MNV Analyze/Animate is the real-time software that views and records the subject. It is also possible to replay, edit, and analyze previously recorded sessions offline after the recordings.

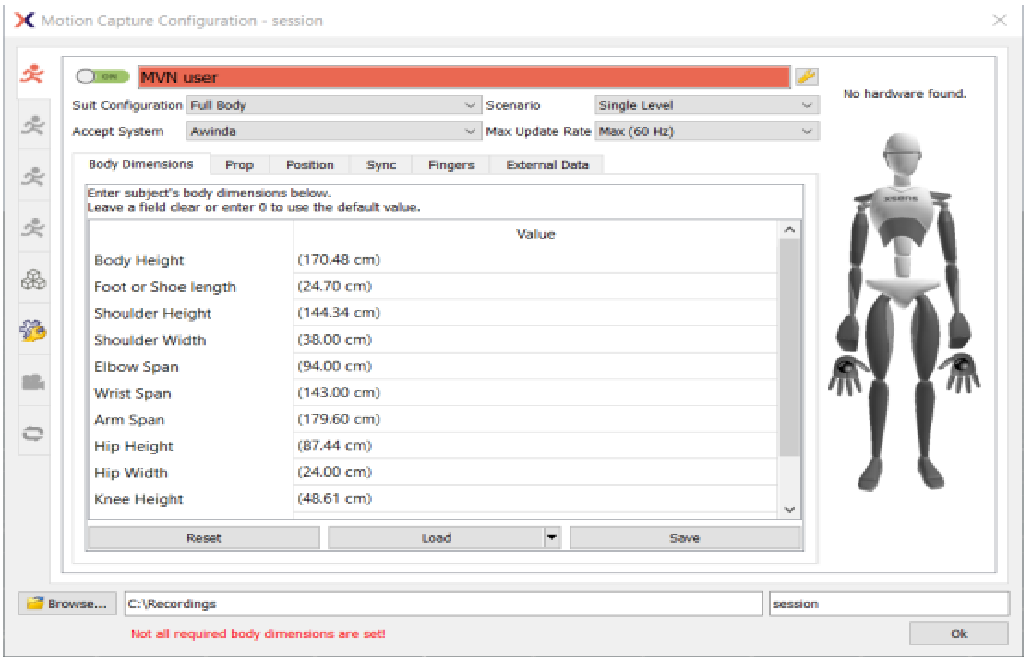


Fig. 5 - MVN interface (from MVN User Manual).

Measurements to be entered:

- Body Height: from the head to the floor.
- Foot or shoe length: foot or shoe length.
- Shoulder Height: from the floor to the C7 spinal process.
- Shoulder Width: the right-left distal tip of the acromion.
- Elbow span: in T position from right to left olecranon.
- Wrist span: in T position from right to left of ulnar styloid.
- Arm span: in T position from the fingertips of the left hand to the fingertips in the right hand.
- Hip height: from the floor to the most lateral bony prominence of the greater trochanter.
- Hip Width: from the right to the left anterior superior iliac spine.
- Knee Height: from the floor to the lateral epicondyle of the femoral bone.
- Ankle Height: from the floor to the distal tip of the lateral malleolus.

After accurately entering the measurements on the software, 17 MTx trackers are mounted using Velcro contained in the back. These motion sensors are miniaturized inertial devices containing 3D linear accelerometers that measure accelerations (including gravitational), integrated 3D gyroscopes that measure angular velocity, 3D magnetometers that measure the Earth's magnetic field, and a barometer, which measures atmospheric pressure. Two types of trackers are identical but have different connectors: MTx, which is single and used as an "end" tracker; MTx-STR, a string consisting of three sensors. The trackers are positioned at specific locations: single MTxs are mounted on the head, sternum, pelvis, and hands, while MTx-STRs are mounted so that the shoulders are concatenated with the arms and the legs with the feet.

In addition to the trackers, the suit consists of a body pack (BP) on which four connectors at the top interconnect four strings of MTxs. Starting from the left is the larger 5-pin connector that connects with the battery; then, two central 5-pin connectors connect the MTx strings. This mechanism retrieves data, ensuring highly synchronized movements; the information is transmitted with an optimized 2.4 or 5.0 GHz spread-spectrum wireless link via Ethernet cable.

Fig. 6 - MTx and MTx-STR (from MVN User Manual).

After the trackers are attached and the body back (BP) is turned on via the push button, on the screen, in the subject's profile, his avatar appears with green status indicators. At this point, they must click "ok" to represent the avatar in the 3D environment.

The next step is to perform biomechanical calibration, which is very important to ensure optimal results at the kinematic level.

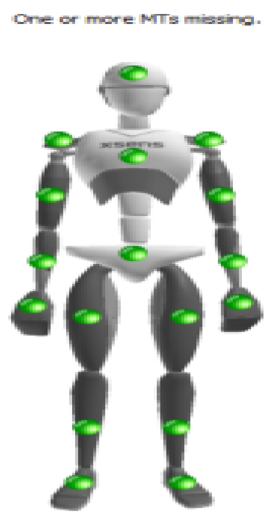


Fig. 7 - status of indicators (from MVN User Manual).

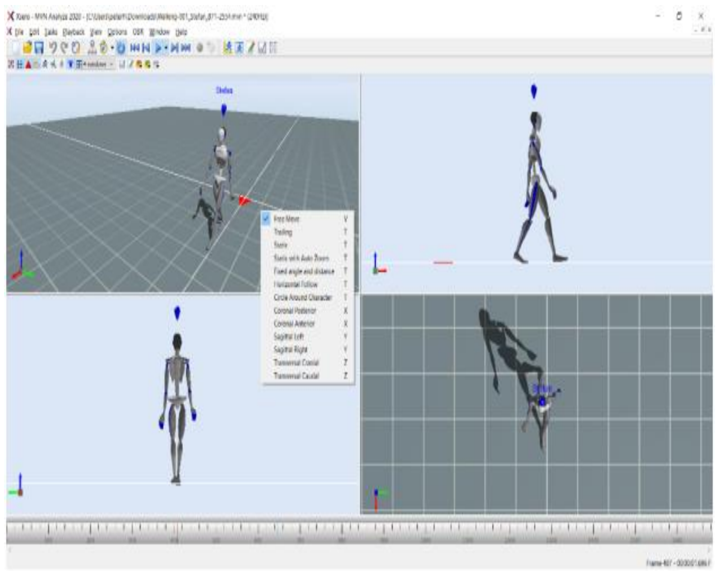


Fig. 8- 3D avatar view (from MVN User Manual).

After calibration, the data is recorded. All files containing subject recordings are exported to an XML format called MVNX, which is imported into Matlab (2022b). Through this format, it is possible to have information about sensor data, segment kinematics, and joint angles. Specifically, it is possible to export information about the 3D position, linear and angular acceleration, and velocity of the 23 segments, the angles of the 22 3D joints, the position of the body's center of mass, data indicating the points that are in contact with the ground, the 3D orientation and free acceleration, and the magnetic field data of all motion trackers.

The MVN Fusion Engine calculates position, orientation, and data for each body segment (B) concerning a global coordinate system (G). By default, the Earth coordinate system is considered a right-handed Cartesian coordinate system with a three-axis reference system:

- X (red): points to the local magnetic north.
- Y (green): right-handed coordinate system.
- Z (blue): pointing upward.

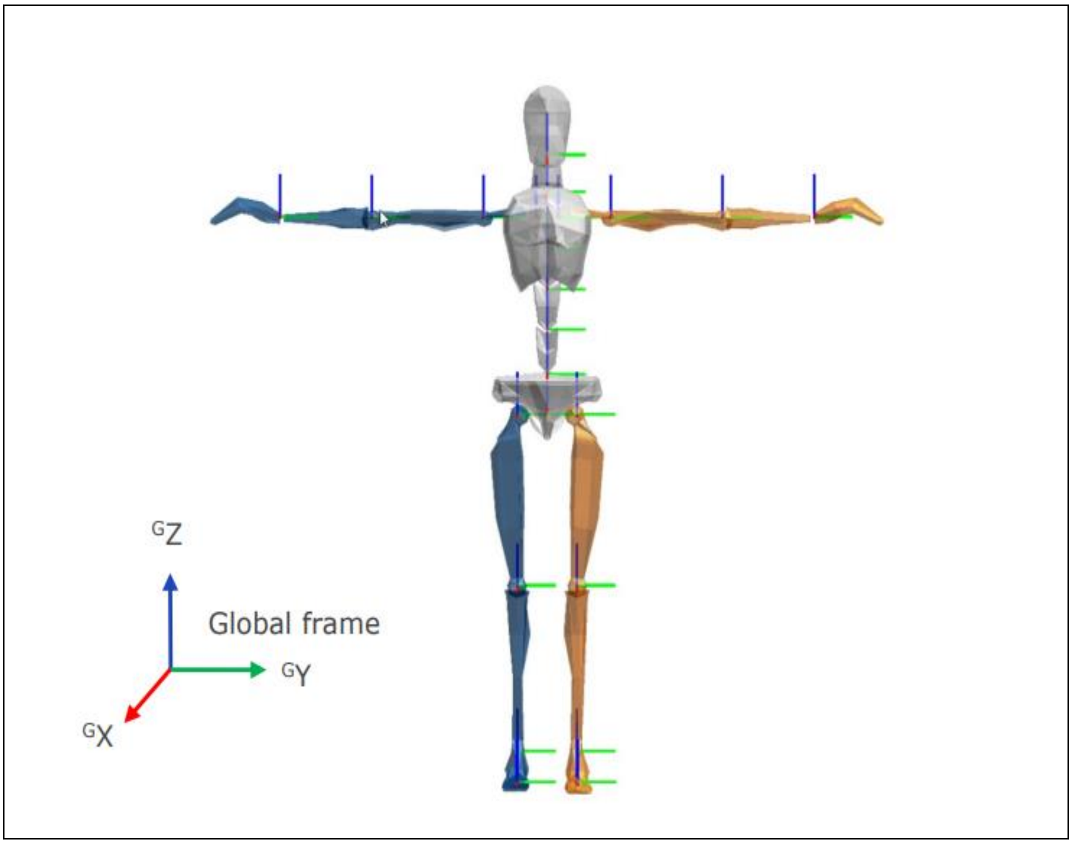


Fig. 9 - Segment coordinate system for each segment source used in MVN(from MVN User Manual).

2.4. Experimental design

The experiment comprises seven motor learning sessions (S1-S7); in three sessions (first, sixth, and seventh), we also have electroencephalography recordings.

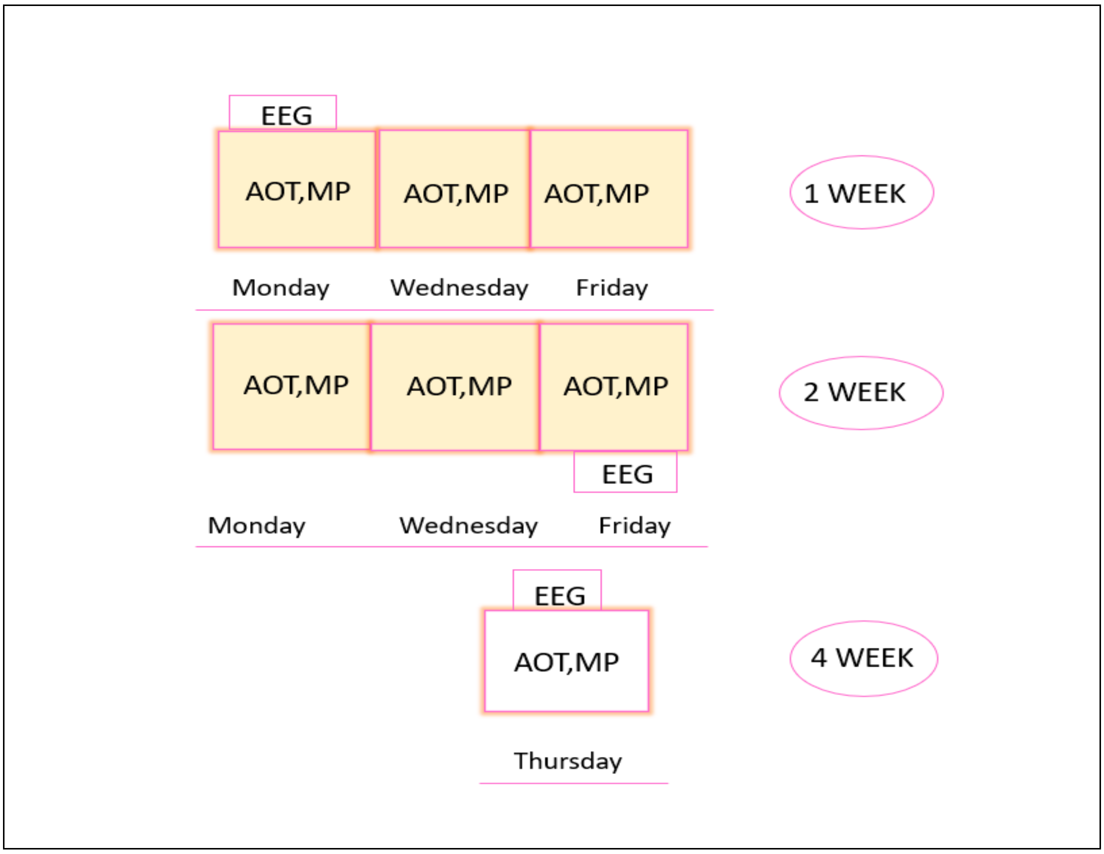


Fig. 10 - Paradigm

Through randomization, two videos are chosen for AOT practice and two videos for MP (motor practice based only on execution) for each participant. We did not change the stimuli of the AOT and MP learning in the seven days of recording, although the order in which they have shown to subjects was changed randomly. The remaining two "naïve" stimuli were presented only in the seventh session with the AOT learning method. In addition, during the seventh session, the participant is asked to watch the stimuli not with the AOT method but is shown only once and asked to perform the practice five times in a row. This happens for each stimulus, so four times in total, the stimuli being the same as those presented during the six sessions.

The sequences of Kinematic recordings: A1=3,A2=5,M1=1,M2=6

A1	A2	M1	M2
M1	M2	A1	A2
A1	M1	A2	M2
M1	A1	M2	A2
A1	M1	M2	A2
M1	A1	A2	M2

Kin-session1	Kin-session2	Kin-session3	Kin-session4	Kin-session5	Kin-session6
5	2	3	1	4	6

Fig. 11- An example of randomized sequences for six sessions of one subject. The stimuli consist of six videos (numbered 1 to 6), and the four that will be used for AOT and MP are chosen randomly. The other two videos will be used during the follow-up session

Learning with AOT consisted of five times alternating video observations (13-18s duration) and execution. In contrast, learning by Motor Practice consisted of one video observation and five executions. To maintain attention, after the first execution, static images were presented for 15 seconds, during which the participant had to perform the sequence respectively. This image presentation and performance procedure is repeated in motor performance learning four times. The request made to the subjects was to execute the motor sequences they observed.

Fig. 12 - One of the static images presented during the session of motor practice.

The subjects sat in a chair in front of a screen and watched the expert's videos. Afterward, they moved to the reference point and stood in the starting position with their hands resting on their thighs. After the performance, the subjects put their hands in the junta position to notify the experimenter that they had finished. In addition, the subjects' performance was recorded through a camera.

Fig. 13- Subject 01; starting position.

2.5. Kinematics data collection and experimental procedure

Kinematic data are recorded through inertial sensors placed on the MVN Lycra suit at various body segments. The motion trackers (MTx) are placed at a specific location: in the head, sternum, pelvis, hands, arms, legs, and feet. Before recording, but only in the first session, measurements of each body part are taken; the measurements are recorded in the subject's profile and retained for all other sessions. The biomechanical calibration is performed before each session. The goal is to align the trackers to the various parts of the subject's body; this is done by asking participants to first position themselves in "Npose," basically a neutral pose, then they are asked to walk forward and back. Before recording, an additional check is made by asking the subject to extend or flex their limbs, bring their feet together, and join their hands. If the calibration succeeds, we move on to the recording with video display and execution. Through Xsens' MNV Analyze / Animate software, a 3D avatar of the subject can be displayed, and its movements recorded. During each session, four stimuli are shown, two by the AOT method and two by the MP method. For each stimulus, the subject performs five executions, so a total of 20 executions are recorded, each of which is recorded individually, so each file Xsens contains only the recording of a single execution. The participant is asked to sit in a chair placed in front of a screen on which the videos will be shown. Afterward, the subject is asked to go to the center of the room, where an "X" is marked on the floor. The position to let the experimenter know he is ready is "Npose." Then, the experimenter starts the recording by saying, "3, 2, 1, go," The subject performs with as much precision as possible the motor acts shown above. Then, he/she returns to the starting position, but in this case, placing his/her hands together.

Each recording is saved as an Xsens file, and it is then necessary to export the files in MVNX format, which allows the files to be opened in Matlab (2022b) to analyze the motor sequences.

2.6. Kinematic Data analysis

2.6.1. Segmentation

The analyses aim to investigate motor learning by comparing the subject's motor acts with the correspondence with the expert's performance; in particular, the data of joint angles during the participants' performances are compared and correlated with those of the expert model.

Joint angles: Movement can have different degrees of freedom for axes, which we measure by joint angle. Thus, we can say that angular motion is determined by the angle variation between the two joint heads. We define the joints analyzed, thirteen in total (including ankles, wrists, elbows, shoulders, knees, hips, and pelvis), as structures that allow connection and movement between two body segments.

Xsens MVN to produce output is based on the recommendations of the International Biomechanical Society (IBS), considers twenty-two joints, and calculates 3D joint angles according to the Euler angles of Z (flexion/extension), X (abduction/adduction), and Y (internal/external rotation).

Flexion occurs in the sagittal plane and causes two body parts to move closer together, thus decreasing the angle between them. For example, during head flexion, the chin moves closer to the chest; during leg flexion, the foot rises backward; and during forearm flexion, the forearm moves toward the shoulder.

The extension also occurs in the sagittal plane but represents the opposite movement to flexion, increasing the distance between two parts of the body and, consequently, the angle between them. For example, one extends the head by raising the chin upward and extends the leg by kicking a ball.

Abduction moves two body parts away from each other in the frontal plane. For example, in the case of the arm, it occurs when the arm is moved away from the body in a 180-degree movement. For the foot, it occurs when the forefoot is brought outward.

Adduction, like abduction, occurs in the frontal plane but represents the opposite movement, in this case occurring when the foot is brought inward, or the limb approaches in the sagittal plane.

The goal is to investigate the similarity of motor acts. As a first step, each motor act should be recognized. Our movements are fluent, without a stop. As a result, we defined a segmentation methodology for identifying each sequence step. To do this, we defined determinator points based on the Expert's motor acts for each subject's session.

Determinator points: Determinator points represent the moment that marks the attainment of the correct position of the motor act. The position of each body segment has a Maximum and a Minimum based on three directions:

- Y: The body segment in the right direction represents the Maximum in that direction. The left represents the Minimum.

- X: The body segment in the front direction represents the Maximum in that direction, behind represents the Minimum.

- Z: The body segment in the upward direction represents the Maximum in that direction, and the down represents the Minimum.

The figure (n.14) below represents an example of a sequence with seven motor acts, the second image represents the achievement of the first act, and the hand to the right represents the Maximum in the Y direction. The third image represents the achievement of the second motor act of the sequence; in this case, the hand in the opposite direction from the previous image represents the Minimum in the Y direction. In addition, both images represent hands upward, thus the maximum in the X direction.

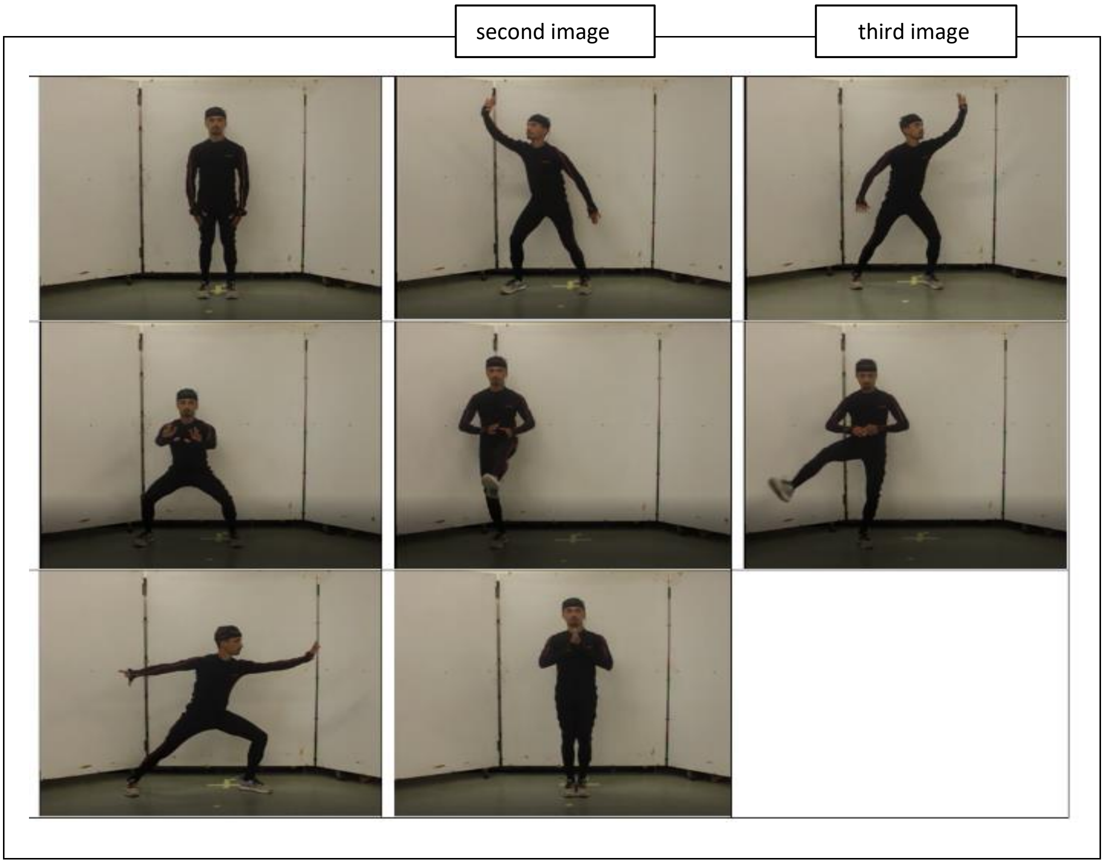


Fig. 14 - Depiction of positions representing the moment of attainment of the motor act (determinator points).

In the following graph (fig.15), a motor sequence is shown with red dots representing possible stopping points of the movement. In addition, there are three signals represented by different colored lines: the blue line represents the trend of the sum of the absolute value of the velocity of the center of mass in the three directions, the yellow line represents the velocity of the forearms while the purple line represents the sum of the hand and leg positions.

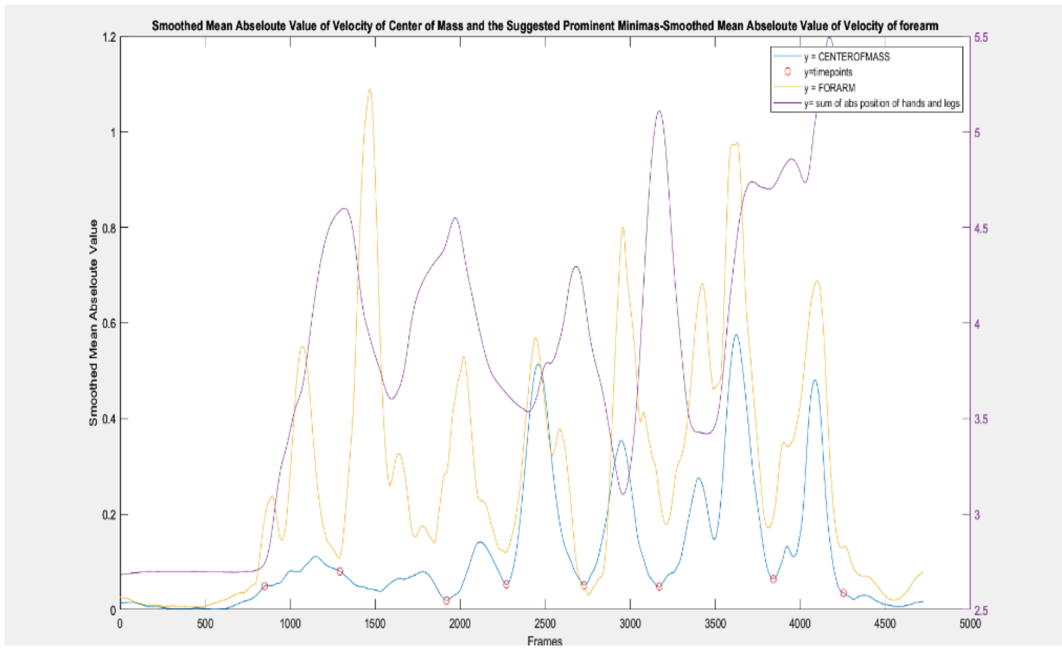


Fig. 15 - Representation (Matlab 2022b) of the smoothed mean absolute value of the velocity of the center of mass and forearms.

In the first step of segmentation, we defined three signals to address the natural reduction in velocity of the subject. The movement has framed as its unit of measurement (each second equals 240 frames).

First signal: The summation of the absolute value of the center of mass velocity in 3 directions. If we have a reduction in velocity that happens naturally at the end of motor acts, we can recognize this drop within this signal. This signal is the benchmark for making the segmentation (Figure 15).

Second Signal: The summation of the absolute value of forearm velocity in 3 directions. In our designed sequences**,** motor acts start with the hand movement and finish with a drop in this velocity. This specific signal can be a more precise signature for recognition of the start and stop of a sequence. So, we add this signal as a supplementary guideline for segmentation.

Third Signal: The summation of the absolute value of hands and food positions in 3 directions. When a participant is in a reduced velocity or steady, the value of this signal has a reduced variation. Consequently, we also add this signal as a supplementary guideline for segmentation.

The movement's progress is checked, and if necessary, a point is removed or added based on where one motor act appears to end and the next begins. If the motor sequence were carried out thoroughly, there should be eight points. But there could be even fewer if a motor act is forgotten or more if motor acts are performed in a segmented manner (this occurs if the participant stops in the middle of the act and then continues).

After assessing the correctness of the first figure, other figures are generated as many as the motor acts. Each one represents an act with a Minimum or Maximum instant of attainment.

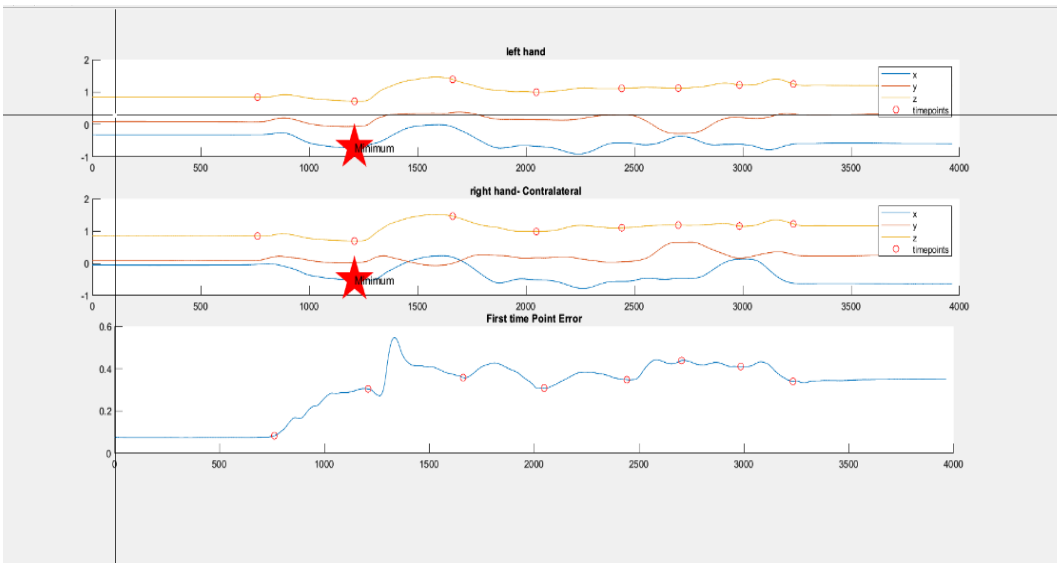


Fig. 16 - Figure generated by motor segmentation representing the first motor act.

The figure shown above (fig.16) represents a motor sequence with eight points representing the beginning and end of each motor act. In particular, the first motor act is shown where there is the star represents the minimum in the Z direction; it represents the hand going downward and resting on the knees.

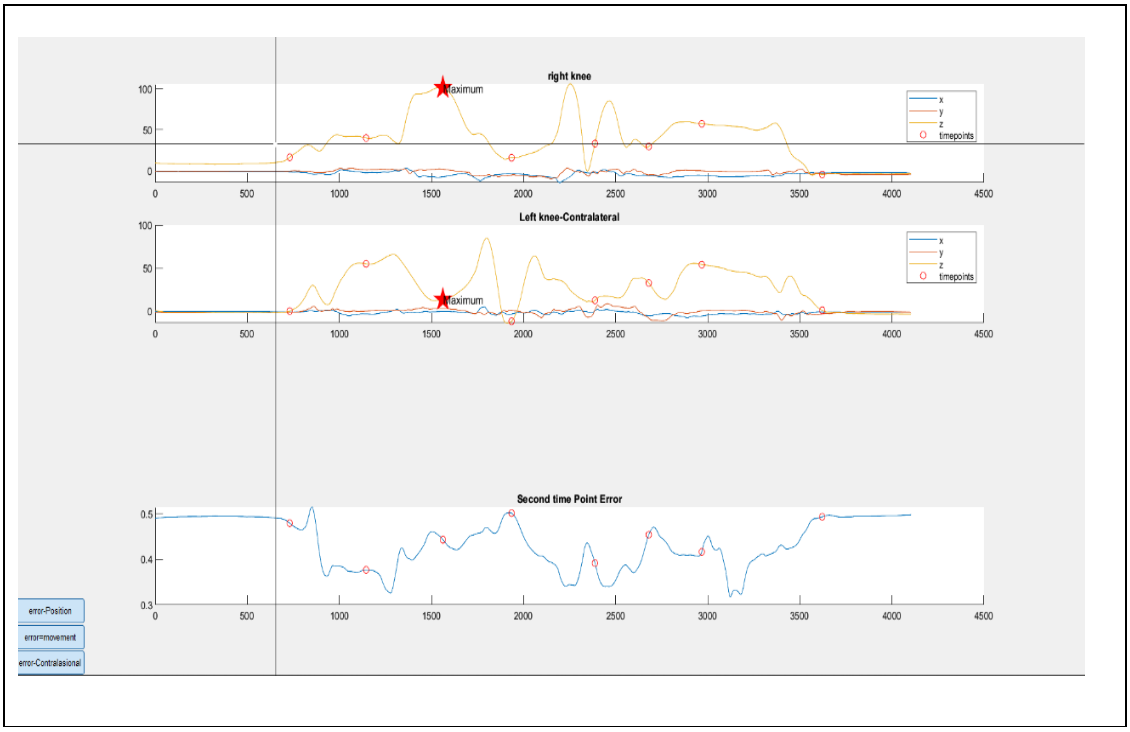


Fig. 17 - Motor act representation, right leg bent with knee upward.

The figure above (n. 17) depicts the flexion of the right knee; in this motor act, the right leg is bent upward (Maximus in the first graph) while the left knee remains outstretched and the leg rests on the ground (Maximus in the second graph).

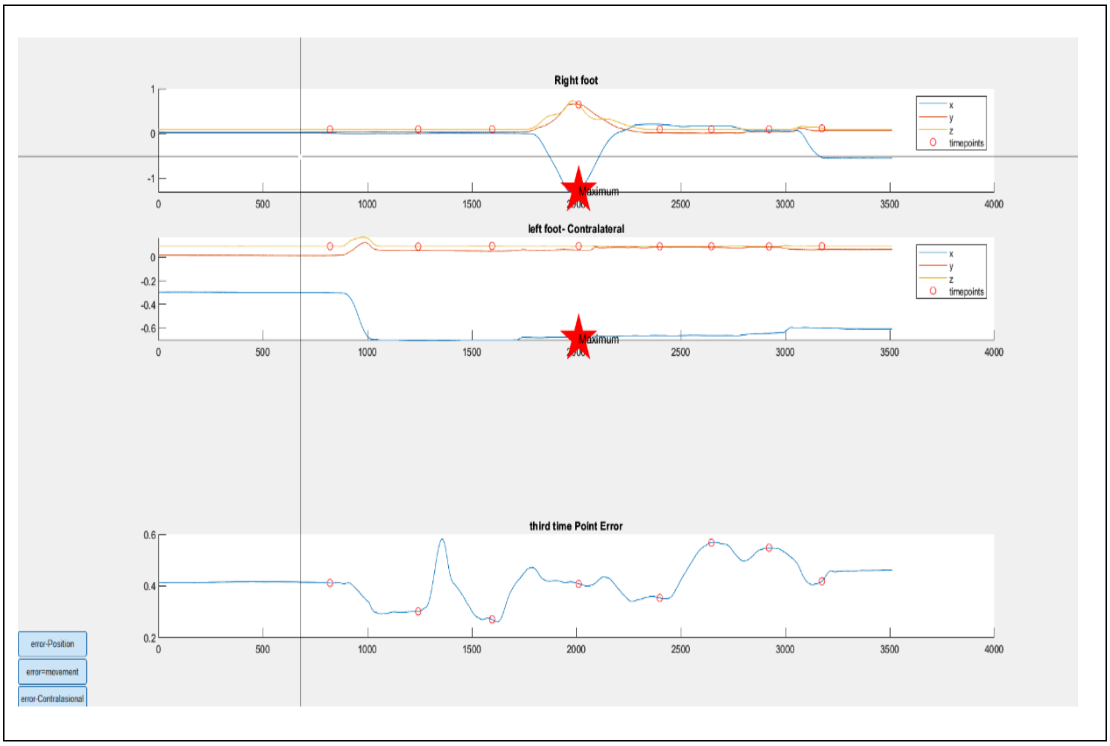


Fig. 18 - Motor act representation, kicking with the right leg to the left.

In this graph (fig.18), the Maximum is represented by a curve going down because it represents the right foot going in the opposite direction, thus toward the left.

The figure below (n.19) shows a "mirror" motor act, that is, performed with the contralateral limbs. The Minimum being indicates this at the top of the curve in the first graph, representing the left knee that should be lying down in the correct motor act so the curve should go downward. The second graph represents the right knee which should be brought toward the chest but, in this movement, is lying flat; therefore, the curve goes downward instead of upward (see figure 17; graphic representation of the correct motor act).

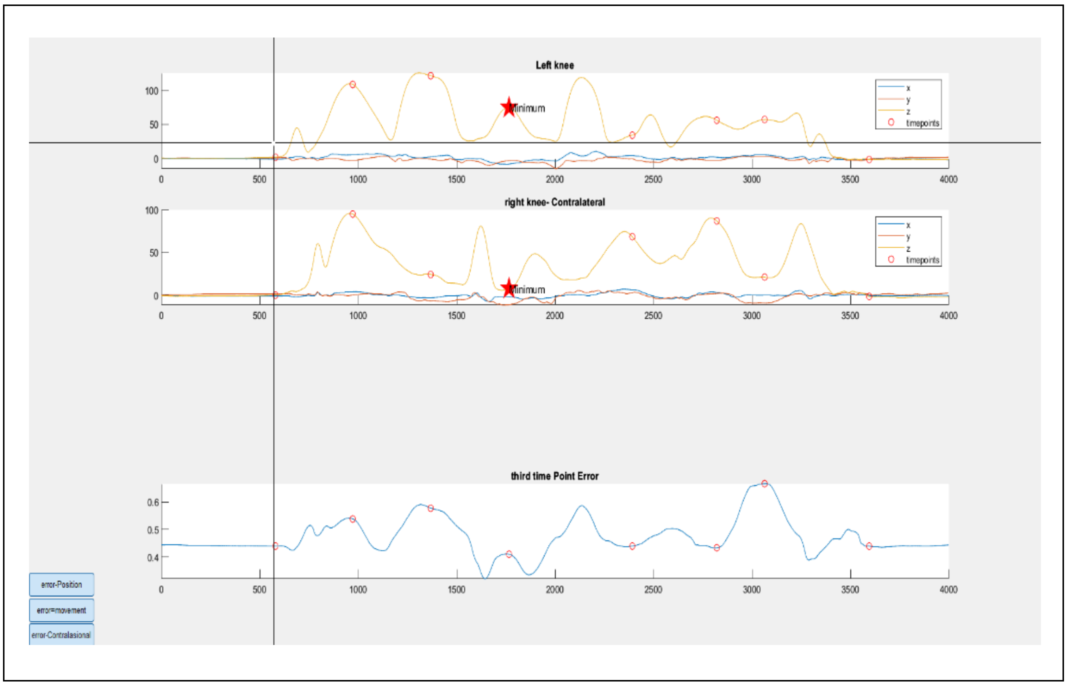


Fig. 19 - Movement mirror.

During the analyses of the various figures, it is possible to change the values representing the instants of motor act attainment (Maximum and Minimum) in case they are not placed at the correct point on the movement curve.

2.6.2. Correlation

After segmenting the sequence into motor acts, correlation scores between the joint angles of the expert and the participant were computed. Pearson's correlation index is used, which expresses a possible linear relationship between two variables. The correlation value could range from +1, which indicates a greater similarity between the participant's motor and the expert's motor act, to -1, indicating a negative linear correlation and, thus, inequality between the motor acts.

$$rho(a,b) = \frac{\sum_{i=1}^{n} (X_{a,i} - \overline{X}_a)(Y_{b,i} - \overline{Y}_b)}{\left\{ \sum_{i=1}^{n} (X_{a,i} - \overline{X}_a)^2 \sum_{j=1}^{n} (Y_{b,j} - \overline{Y}_b)^2 \right\}^{1/2}},$$

The correlation returns a matrix with pair correlation coefficients between each pair of columns in the X and Y matrices. Since each session contains seven motor acts, we will create a 7x7 matrix to look at the values diagonally representing the correlation between the corresponding motor acts (first column and first row, second column and second row, and so on).

	1	2	3	4	5	6	7
1	0,5110	0,0447	0,0438	-0,3130	0,2012	0,2068	-0,2174
2	-0,1034	0,5277	-0,2779	0,1942	-0,1063	0,4144	-0,1836
3	0,0856	0,2068	0,3647	-0,0592	-0,0218	0,0044	0,1425
4	-0,1869	-0,0668	0,0307	0,3275	-0,0511	-0,2526	0,1987
5	-0,0254	-0,1306	0,1636	-0,2533	0,4983	-0,1124	0,0388
6	-0,2173	0,3081	-0,2910	0,0211	-0,1079	0,4540	-0,5277
7	0,0912	-0,2726	0,1140	-0,0231	0,0997	-0,3557	0,4958

Fig. 20 - Correlation 7x7 of a motor sequence

In addition, if it is deemed necessary after obtaining the correlation, we can change the values of the frames on the Matlab timepoint table. (fig.14) and compare them with the offline recording on Xsens MNV. The first value corresponds to the start of the movement from the starting position; the second value corresponds to the end of the first motor act; the third value to the end of the second; and so on to the third value. Simultaneously, one goes to check on the Xsens MVN software that the values in frames coincide, and if not, the correct values are entered, so that true correlations are then generated.

Timepoints1	
1	744
2	1190
3	1597
4	1980
5	2454
6	3010
7	3253
8	3779

Fig. 21- Timepoints in frames of a motor sequence

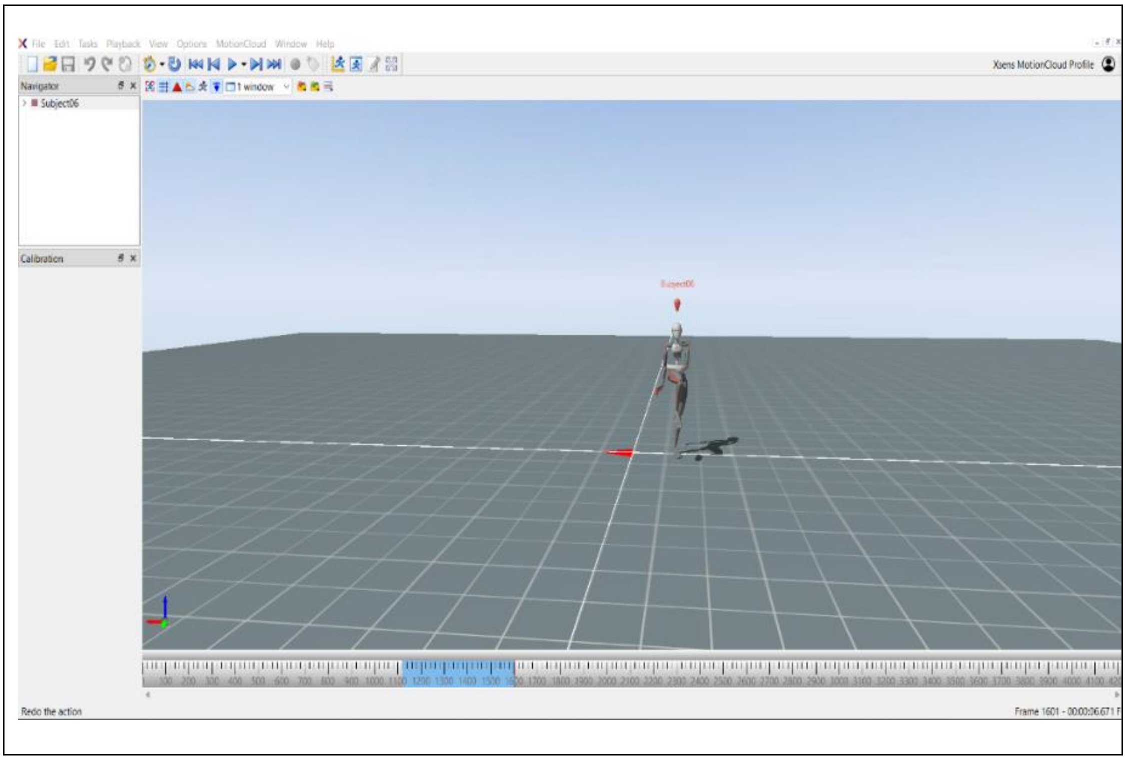


Fig. 22 - Offline visualization of a motor sequence

2.6.3. Calculation of Score

As explained earlier, the participant's joint angles are compared with the expert's; with Pearson's correlation, a diagonal of seven values is obtained. Then, for each trial, we have seven values corresponding to the seven motor acts of Expert in the diagonal of a Correlation matrix.

After that, an average is taken off the diagonal (from the seven elements on the matrix diagonal). From this, we get a value representing the trial performance. At this point, the average of the five repetition trials is further averaged to derive a score representing a given stimulus's performance. This operation is done for the four performances of the four stimuli presented during each session; two represent learning by Action Observation Training (AOT), and two represent learning by Motor Practice (MP), so we will have four values for each session.

After these operations, it is possible to calculate the learning scores for seven sessions and evaluate their performance so that four patterns can be obtained. In addition, the average of the two AOT values and the average of the two MP values can be averaged; in this way, a graph can be obtained that follows the performance of the seven sessions, with two lines representing the overall performance in AOT and MP. In addition, the two AOT values of the first session can be averaged and compared with the two naive AOT values of the seventh session. In the end, we also average the trends of all workouts and present the figure in the results section.

Through the correlation values, I calculated the learning rate (LR) of the two conditions, AOT and MP. This indicator shows how much the participant learned during the training from the first to the sixth session; this is calculated by subtracting the correlation value of session six from that of session 1 (LR = S6 - S1). Then I calculated the decay rate after the training (DECAY = S7 – S6), i.e., the learning lost after the two-week break. From these two results, obtaining the percentage of learning consolidation [CL = (1-DECAY/LR) *100] is possible, thus consolidated learning at follow-up.

3. RESULTS

3.1 General results

The results reported in this chapter are descriptive of three subjects and represent the learning and the degree of similarity between the participants and the expert model.

The figure below (fig.23) shows a single trend representing the overall average of the performance correlation scores in both the Action Observation Learning (AOT) and Motor Practice (MP) learning conditions of the three subjects during the seven sessions. As can be seen, general learning is present, and the seventh week shows slightly lower values; this can be explained by the fact that it was conducted in week four (follow-up) two weeks after the training.

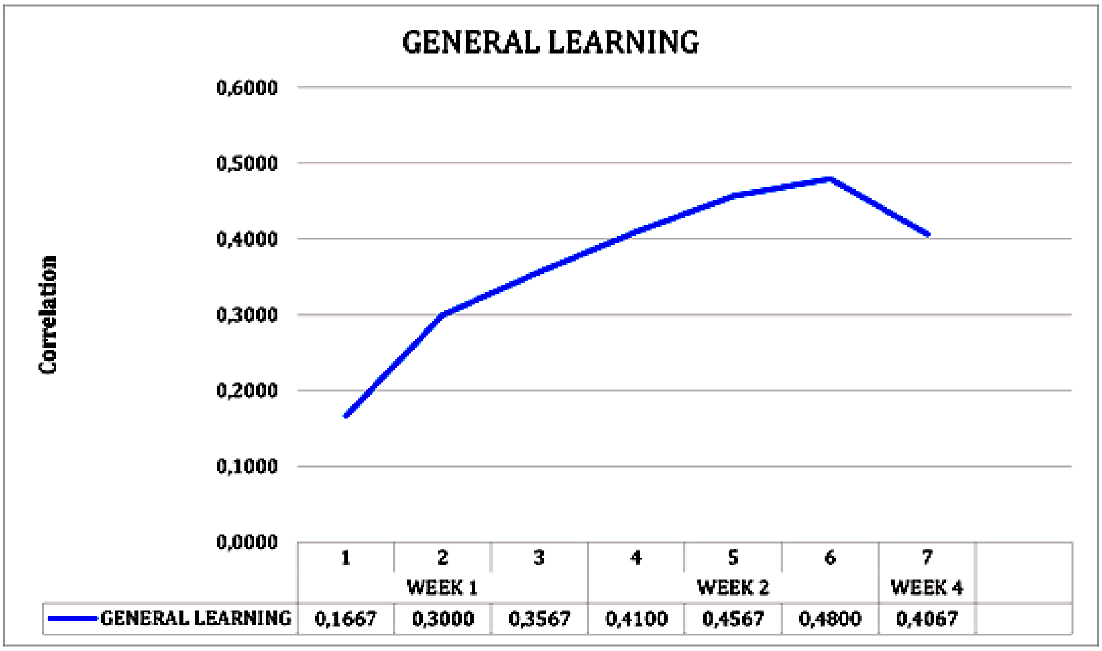


Fig. 23- Average of the correlations of the three subjects and average of the AOT and MP conditions in the seven sessions

The figure below (fig. 24) represents the average of the three subjects in the two learning conditions Action Observation Training (AOT) and Motor Practice (MP). From the graph, we can see that with both the AOT and MP methods, the learning level of the three subjects increases from the first day to the sixth day of training. To be precise, the learning rate for the former method is LR_{AOT} = 0.3267, while for the latter is LR_{MP} =0.30). In contrast, the decay value, the learning lost after a two-week break since the last training, is higher in the MP method ($DECAY_{MP}$ = 0.1333) than in the AOT method ($DECAY_{AOT}$ =0.0133). We can say that Action Observation training (AOT) was more effective than the motor practice (MP) method. This result is confirmed in the analysis of the percentage of learning consolidation for the AOT method is CL_{AOT} = 95.92%, while for the MP method, it is CL_{MP} =55.56%. In addition, a learning generalization effect is noted, as can be seen in the average correlation values of the naïve sequences (0.2477) performed during follow-up are higher than those of the sequences performed during the first session (0.1400).

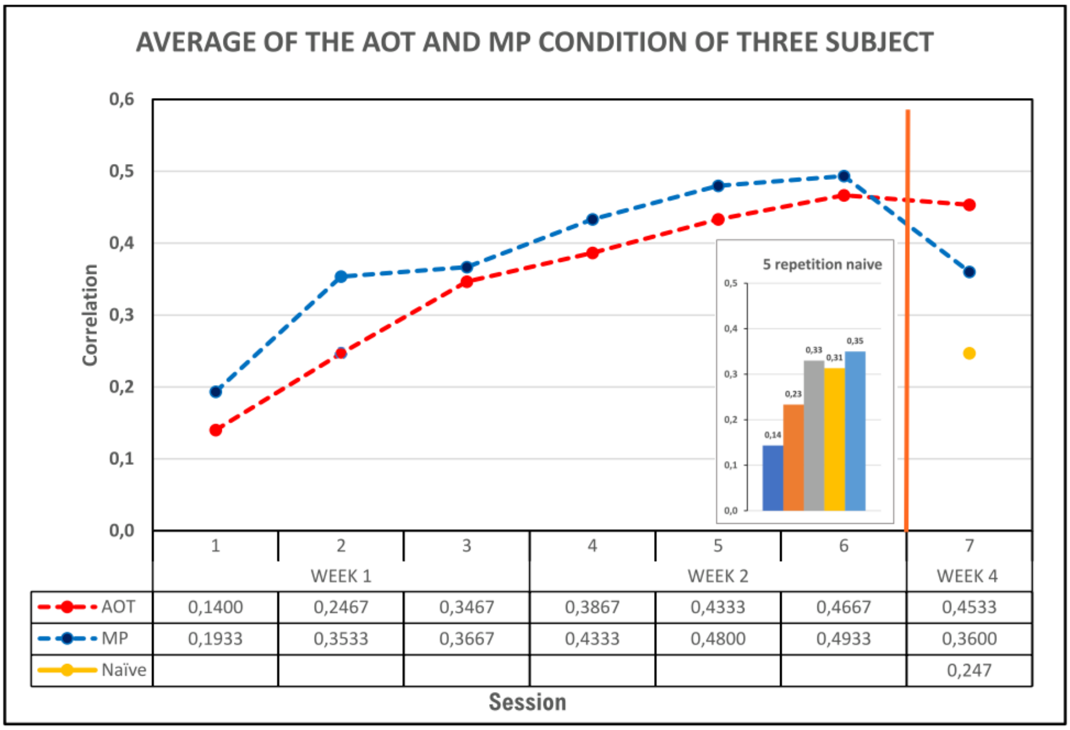


Fig. 24 - Average of the correlation values of the three subjects in the AOT and MP conditions; Average of the five repetitions in the AOT naïve condition. Informative histogram of the correlation values of the five naive repeats.

3.2 Results of individual subjects

The following graphic (fig. 25) reports the results for subject 1. In particular, we can see two similar trends, with slightly lower values for the MP method. The learning rate value for the AOT method is 0.4400 (LR_{AOT} = S6-S1), while for the MP method, it is 0.2867 (LR_{MP} =S6 - S1). While the decay value (DECAY = S7 - S6) is higher in the MP method ($DECAY_{MP}$ = 0.0200) than in the AOT method ($DECAY_{AOT}$ =0.0067). The learning consolidation rate is very good for both methods, in detail the AOT method is 98.49% [CL_{AOT} = (1-$DECAY_{AOT}$/LR_{AOT}) *100], while for the MP method, it is 93.02% [CL_{MP} = (1-$DECAY_{MP}$/LR_{MP}) *100]. The subject shows a generalization effect during the fourth week, as the average correlation values of the five naïve repetitions are higher (0.3140) than those of the AOT sequences in the first session (0.1000). In the case of subject 1, Action Observation training (AOT), although it had lower scores in the first session than MP, was more effective both during the training and in the follow-up.

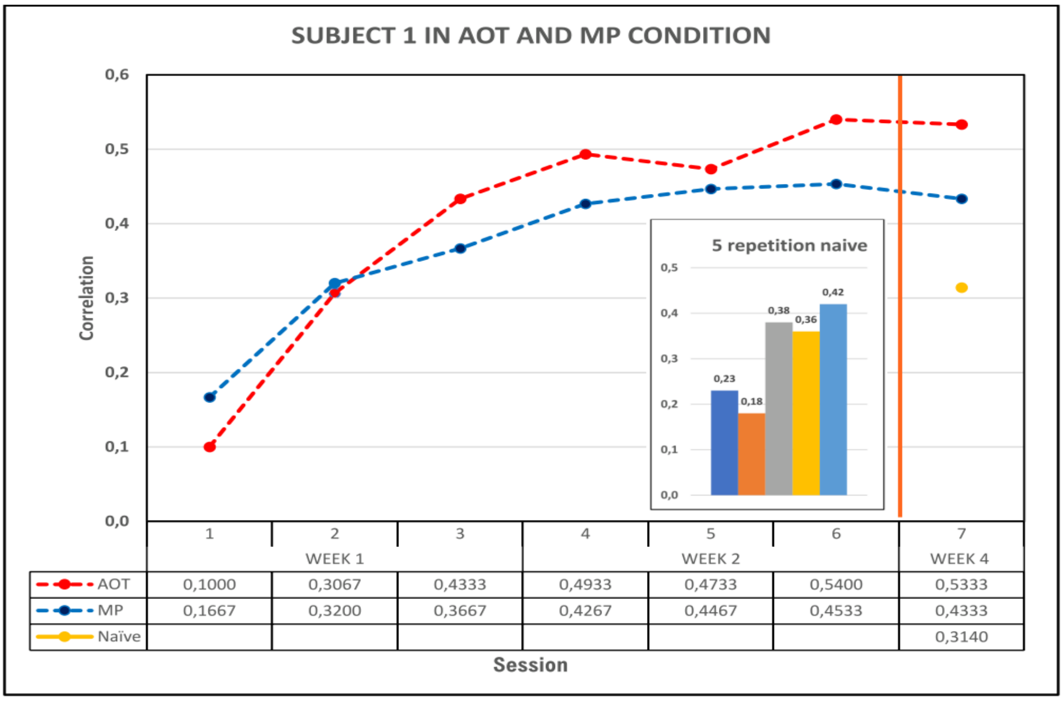


Fig. 25 -Average of the correlation values of subject 1 in the two conditions AOT and MP; Average of the five repetitions in the AOT naïve condition. Informative histogram of the correlation values of the five naïve repeats.

The figure represents (25.1), more specifically, the performance trends of subject one concerning the correlation values of the executions of the four stimuli, two by the AOT method and two by the MP method. It is possible to note the learning variabilities among the various sequences; what stands out is that the values are greater for one of the two AOT stimuli than for the others.

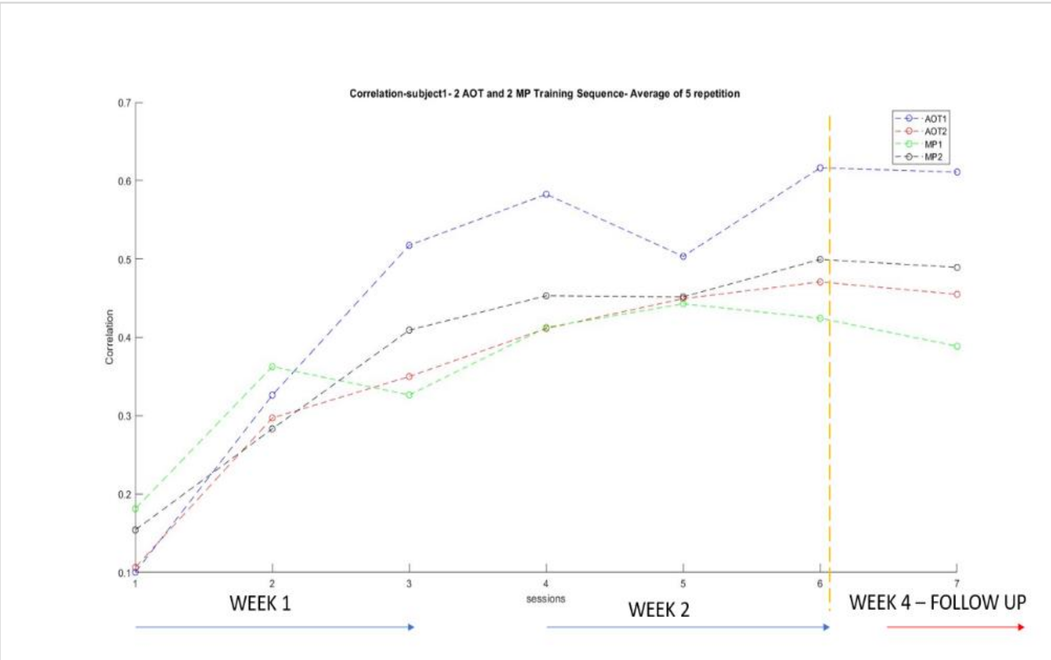


Fig. 25.1 The trends of subject 1's performance regarding the correlation values of the executions of the four stimuli, two using AOT and two MP methods, are depicted.

Figure (n.26) represents the data of subject 2. As can be seen, MP has higher learning values during the six-session training first two weeks; this is demonstrated by the learning rate value, which in the MP method is 0.4000 (LR_{AOT} = S6-S1) while the AOT value is 0.3125 (LR_{MP} =S6 - S1). During follow-up, however, the score decreases exponentially; the decay value (DECAY = S7 - S6) is far higher in the MP method ($DECAY_{MP}$ = 0.23) than in the AOT method ($DECAY_{AOT}$ =0.019). As a result, the learning consolidation rate for the AOT method is far better at 94% [CL_{AOT} = (1-$DECAY_{AOT}$/LR_{AOT}) *100], while for the MP method, it is 42.19% [CL_{MP} = (1-$DECAY_{MP}$/LR_{MP}) *100]. Moreover, a generalization effect of learning can also be seen in the case of subject 2; In fact, the score of the mean of the executions of the naïve AOT stimulus performed in the seventh session is (0.256) while the score during the first session is (0.0875); The histogram represents the correlations of the five repetitions. In summary, we can say that training consolidation proved to be greater in the AOT condition while maintaining similar correlation scores to the previous sessions. This finding favors the effectiveness of AOT as a learning method.

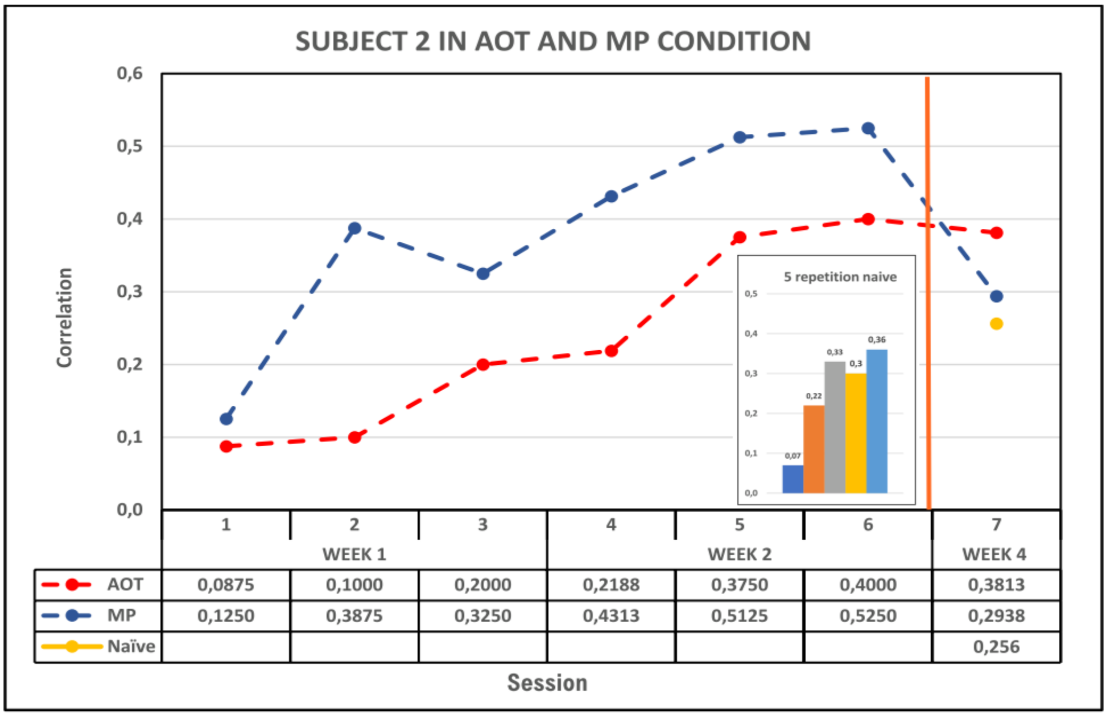


Fig. 26 - Average of the correlation values of subject 2 in the two conditions AOT and MP; Average of the five repetitions in the AOT naïve condition. Informative histogram of the correlation values of the five naïve repeats.

Figure (26.1) shows subject 2's data regarding correlation scores related to learning the four stimuli during the seven sessions. Visible is a better performance score regarding learning both MP stimuli until the sixth session, while learning the AOT stimuli has lower scores. The change in scores during the seventh session is most visible in this graph; both MP performance scores are lower than in the sixth session, while AOT scores remain stable.

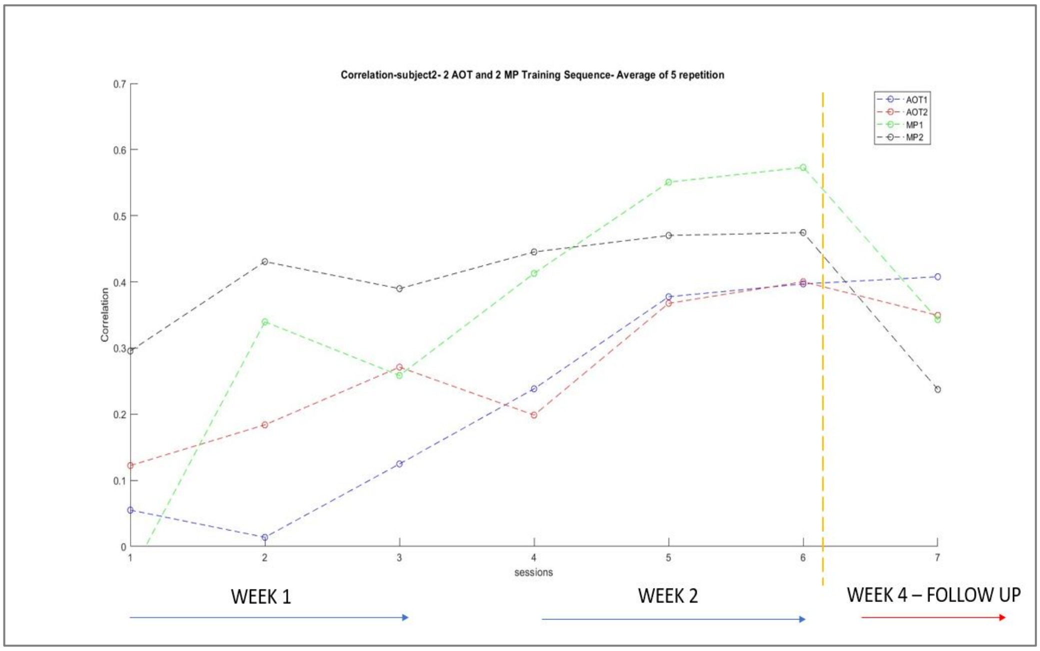
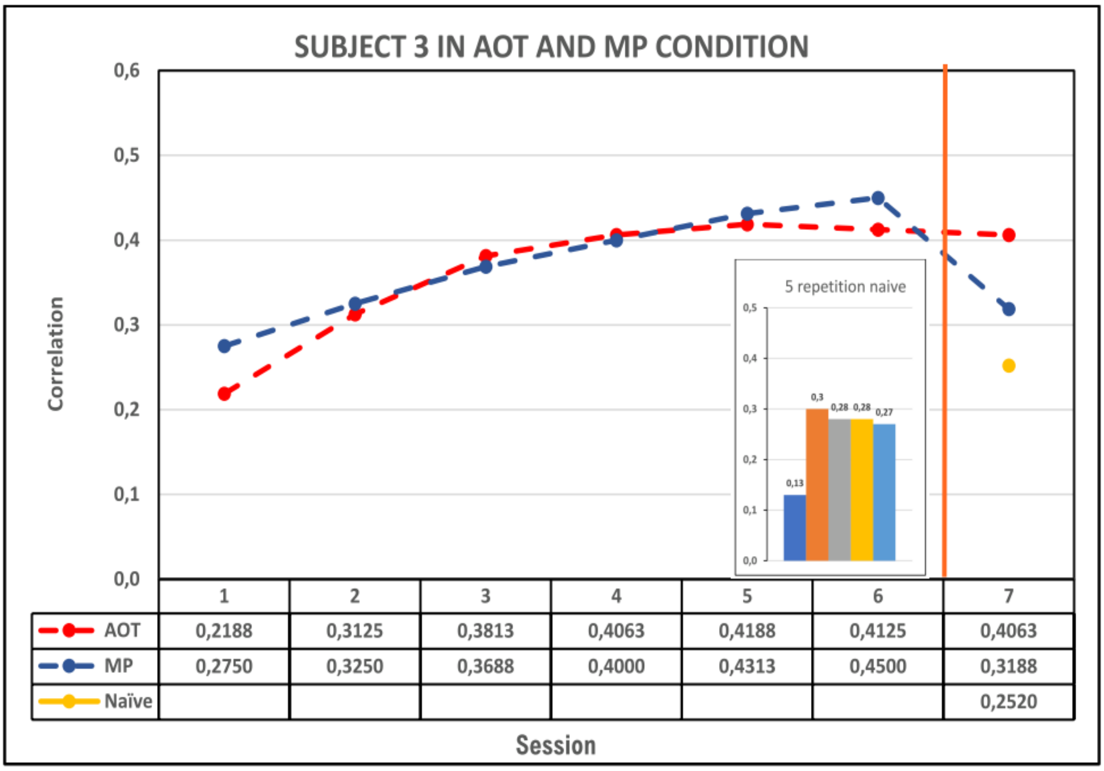


Fig. 26.1 *Subject 2 correlation scores related to learning of the four stimuli during the seven sessions.*

Subject 3 (fig. 27) has very similar correlation values in both the AOT and MP conditions during the six sessions. As can be seen, the correlation values during the first session are already quite high. Already from the graph, it can be guessed that there is a constant learning value growth in both cases. This is confirmed by the learning rate value, which for the AOT method is 0.1938 (LR_{AOT} = S6-S1) and for the MP method is 0.1750 (LR_{MP} =S6 - S1). During follow-up, the AOT values maintain the same trend, as shown by the decay value ($DECAY_{MP}$ = 0.0062), while the MP value drops dramatically ($DECAY_{AOT}$ =0.1313). The learning consolidation rate for the AOT method is 96.77% [CL_{AOT} = (1-$DECAY_{AOT}$/LR_{AOT}) *100], while for the MP method, it is significantly lower at 25% [CL_{MP} = (1-$DECAY_{MP}$/LR_{MP}) *100]. Subject 3 also shows an effect of learning generalization during the first session in the AOT condition has a lower correlation value (0.13) than the value of naïve performance during the seventh (0.2520).



	1	2	3	4	5	6	7
AOT	0,2188	0,3125	0,3813	0,4063	0,4188	0,4125	0,4063
MP	0,2750	0,3250	0,3688	0,4000	0,4313	0,4500	0,3188
Naïve							0,2520

Fig. 27 - Average of the correlation values of subject 3 in the two conditions AOT and MP; Average of the five repetitions in the AOT naïve condition. Informative histogram of the correlation values of the five naïve repeats.

Figure (27.1) shows the performance trend of subject three during the seven sessions. The four lines represent learning the four stimuli, two with AOT and two with MP training. As can be seen, the performances of the four stimuli have similar scores from the first to the sixth session. In contrast, during the seventh session, the correlation of one MP stimulus drops.

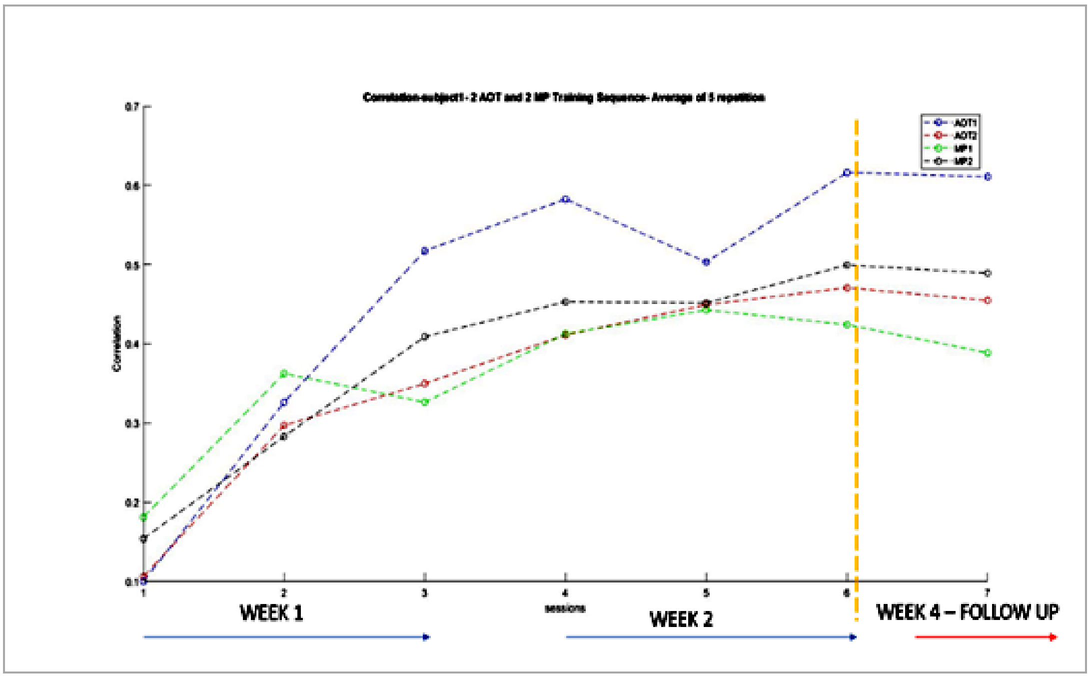


Fig. 27. 1 *Performance trend of subject three during the seven sessions.*

Overall, we can see that the three subjects presented different conditions during the two weeks of training. As for subject 1, he reported higher correlation scores in the AOT condition than in the MP condition. Subject 2 presents an opposite condition with better scores in the MP condition, while subject 3 maintains a similar trend in both conditions. Interestingly, all three subjects show a decrease in correlation values in the MP condition while maintaining the same trend in the AOT condition. Both subject 01 (98.49%), subject 02 (94%), and subject 03 (96.77%) have a consolidation rate that goes over 90% for the AOT stimuli. The three subjects, two weeks after the end of the training, remembered the stimuli learned with the AOT condition better than the MP condition. This result suggests that AOT, for these subjects, was a more effective method than MP. In addition, they all demonstrated a generalization effect of learning, reporting better correlation scores when performing the untrained stimuli performed during follow-up with the AOT method than those reported during the first session of performing the AOT stimuli.

4. DISCUSSION

The present study aimed to achieve two objectives. The first was to investigate the effectiveness of Action Observation Training as a method of learning new motor skills compared to Motor Practice. The second was to evaluate the generalization effect of AOT learning at the end of the training.

Comparing the two learning methods, we observe that both promote learning, as even physical practice improves motor skills. In the three subjects analyzed, during the follow-up, it is observed that there is greater consolidation of motor sequences with the AOT method that remains stable from the sixth to the seventh session. Therefore, in the AOT condition, there is a consolidation rate that is 95.92%, while in the MP condition, this rate decreases to 55.56%. Some variability is observed in the learning trend during the six sessions in the three subjects whose performance was analyzed: subject 1 shows better learning, thus greater similarity to the model, during the execution of the AOT stimuli; subject 2 shows an opposite situation to the first with better learning during the execution of the MP stimuli; and subject 3 shows similar scores in both learning conditions.

The literature reports that the effectiveness of AOT is already present at the early stages of learning (Gatti et al. 2013). Sakadjian's (2014) study investigates, through whole-body kinematic recording, the acquisition of new motor skills in a four-week weightlifting task. Also, in this study, AOT was shown to be more effective than the traditional method as early as the first week. In contrast, during the fourth week, no significant difference was observed in the performance of the AOT and MP groups, but this, as the authors explain, could be due to maintaining the same weight during training. However, in the present study, to assess whether AOT results in faster learning than MP, it is necessary to wait until the end of the recruitment and respective analyses. For the time being, what is observed is a better long-term consolidation in the AOT condition.

The effectiveness of AOT in consolidating other sports skills compared to MP has been demonstrated by other studies, including that of Kim et al. (2011), who specifically analyzed golf putting practice. In the study mentioned above, a different paradigm was used than the one described in this paper; in this case, subjects are divided into two groups, one performing AO and the other MP training. Three sessions are conducted during three consecutive days, and both groups undergo 20 minutes of practice; after one day, the post-test is conducted, and after one week, a retention test is conducted. What emerges is that AOT has greater effectiveness already during the training sessions, but this is even more evident from the analysis of the AOT group's scores during the retention test, which is higher than the post-test.

Although the present work does not report an analysis of neural correlates, it is possible to try to give a neurophysiological explanation for the effectiveness of AOT as a learning method. Action observation and execution activate the frontoparietal network of AON (Buccino et al., 2004). Then, AOT benefits both from the changes of neuronal activity induced by observation, which, even in isolation, activate sensorimotor regions leading to neuroplasticity and the formation of motor memory (Stefan et al. 2005). Moreover, AOT also benefits from the neuronal changes induced by motor practice leading to the acquisition of more efficient learning. Cortical and subcortical connections in the premotor and parietal areas are enhanced by activation induced by observation and execution. Thus, better execution at the behavioral level could result from projections starting from the premotor cortex (Rizzolatti et al. 2014).

In addition, in the present study, we wanted to investigate the phenomenon of generalization of motor learning. In fact, in the three subjects analyzed, generalization could be observed in that during the follow-up, all of them performed more accurately on the untrained stimuli than on the stimuli presented during the first day of the training. This phenomenon can be explained by Schmidt's (1975) theory which is based on the notion of schema involving the use of recall memory to perform a previously learned movement and recognition memory to verify the correctness of the movement. According to this theory, the execution of a given action involves a generalized motor program that can be retrieved in memory and then adapted to another situation. The variability in the motor practice, such as the one in the present experiment, leads to the retention and transfer of information and, thus, to the subsequent generalization of the learning to another novel and untrained sequence.

Evidence supporting this theory has been provided by King and co-workers (2019), who show that new information can be learned more easily if the practice occurs in a domain that is compatible with the previously learned information and thus has consistency with the acquired knowledge. The paradigm of these authors is different from ours in that they are learning motor sequences to be performed on a computer keyboard, so they are not motor sequences performed with the whole body. In the above study, during the first session, participants learn sequences. In the second session, which is conducted the following day, they repeat the learned sequences and learn new ones, which is observed in this facilitation in performance. Another interesting result is that the execution of the previous performance is not interfered with, indicating that the new motor information can be incorporated into the already established memory.

5. CONCLUSION

The reported data show the effectiveness of AOT over MP as a method of learning new motor skills and highlight its key role in the consolidation process. It also shows how a generalization effect can be useful for learning new motor sequences and transferring acquired knowledge to new stimuli.

The thesis reports results related to kinematics, but the project in its entirety (as described in the experimental design) accompanies kinematic data with the recording of EEG data. Therefore, it would be interesting to evaluate whether cortical connections during the resting state in the first session predict good or bad future learning. In addition, EEG results at the end of training and during follow-up may reveal changes due to learning and give a neurophysiological explanation for the kinematic outcome.

Several studies in the literature demonstrate the effectiveness of AOT as a rehabilitation method in various pathologies, especially those involving motor deficits. Consider, for example, pathologies such as Infant Cerebral Palsy in which children with hemiplegia improve their motor performance due to AOT.

In the future, it would be useful to investigate whether the phenomenon of generalization may also be present in the rehabilitation setting, whereby following an improvement in a particular motor task may facilitate performance in other motor tasks useful for performing normal daily actions. The limiting factor in this study is the sample size, which consists of only three subjects whose data are insufficient to state or report significant results. It will be necessary to complete the recruitment and respective analyses to obtain more generalizable results.

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