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DEVELOPMENT OF A HUMAN-ANIMATION INTERACTION SYSTEM TO EVALUATE SYNCHRONIZATION, PREDICTION AND IMPLICIT LEARNING

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DEVELOPMENT OF A HUMAN-ANIMATION INTERACTION SYSTEM TO EVALUATE SYNCHRONIZATION, PREDICTION AND IMPLICIT LEARNING

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Yağmur Ersan Polat

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ABSTRACT

DEVELOPMENT OF A HUMAN-ANIMATION INTERACTION SYSTEM TO EVALUATE SYNCHRONIZATION, PREDICTION AND IMPLICIT LEARNING

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Master of Science, Mechatronics Engineering

Supervisor:

December, 2022

Social interaction in humans is difficult and complex to understand. The main motivation of this study is to construct a human-animation interaction experimental setup to understand social interaction. For establishing the relationship between implicit learning and haptic interaction, haptic guidance and disturbance are added to the experimental setups, its effect on implicit learning was revealed using metrics and statistical tools. It has been observed that the resistive haptic interaction positively affects the existence, transfer and permanence of implicit learning.

Keywords: Social interaction; synchronization; implicit learning; haptic interaction

ÖZET

SENKRONİZASYON, TAHMİN VE ÖRTÜK ÖĞRENMEYİ DEĞERLENDİRMEK İÇİN İNSAN-ANİMASYON ETKİLEŞİM SİSTEMİNİN GELİŞTİRİLMESİ

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İnsanlarda sosyal etkileşimi anlamak zor ve karmaşıktır. Bu çalışmanın ana motivasyonu, sosyal etkileşimi anlamak için bir insan-animasyon etkileşimi deney düzeneği oluşturmaktır. Örtük öğrenme ile dokunsal etkileşim arasındaki ilişkiyi kurmak için deney düzeneklerine dokunsal rehberlik ve rahatsızlık eklenmiş, örtük öğrenme üzerindeki etkisi metrikler ve istatistiksel araçlar kullanılarak ortaya konmuştur. Dirençli dokunsal etkileşimin örtük öğrenmenin varlığını, transferini ve kalıcılığını olumlu yönde etkilediği gözlemlenmiştir.

Anahtar Kelimeler: Sosyal etkileşim; senkronizasyon; örtük öğrenme; dokunsal etkileşim

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To My Family…

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LIST OF ABBREVIATIONS

SI	Social Interaction
GSIC	General Social Interaction Cycle
LF	Leader Follower
MG	Mirror Game
VP	Virtual Player
HP	Human Player
HI	Haptic Interaction
AHI	Assistive Haptic Interaction
RHI	Resistive Haptic Interaction
HI+	Haptic Guidance
HI-	Haptic Disturbance
HG	Haptic Guidance
IL	Implicit Learning
IM	Implicit Memory
IML	Implicit Motor Learning
IK	Implicit Knowledge
EL	Explicit Learning
EM	Explicit Memory
EK	Explicit Knowledge
ANOVA	Analysis of Variance

SRT	Serial Reaction Time
AGL	Artificial Grammar Learning
LCR	Learning of Conditional Responses
AIC	Acquisition of Invariant Characteristic
PLP	Perceptual Learning Paradigm
LPC	Learning of Perceptual Categories
SLA	Second-Language Acquisition
PL	Probability Learning
DSC	Dynamic System Control
CTT	Continuous Tracking Task
IAE	Integrated Absolute Error
RMSE	Root Mean Square Error
MRE	Mean Radial Error
RMS	Position Temporal Correspondence
EMD	Earth Mover’s Distance
CV	Circular Variance
SE	Shannon Entropy
SL	Similarity Level
MPC	Model Predictive Controller
FEP	Free Energy Principle
DMSDS	Double Mass Spring Damper System
FBD	Free Body Diagram

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CHAPTER 1

INTRODUCTION

Humans are sociable creatures by nature as are the majority of animals like ants and bees. That is how nature works. Thanks to this inevitable feature of being alive, almost all living things exhibit social behaviors. Such dynamic series of behaviors are called social interaction in sociology. Social interaction (SI) can be defined as the process through which we modify our actions and reactions according to people around us. It is possible to classify SI as follows: unintentional, repetitive, regular, and controlled. Therefore, we need to be synchronized and predict in order to display these sociability behaviors.

Physical actions, nonverbal cues, verbal exchange, playing, sharing, and other activities are all part of SIs. For the emergence of socialization behaviors, there may be times when we may need some features like language, listening and observation skills. Moreover, to interact socially, synchronization is required. As for synchronization, it can be defined as the simultaneous coordination of several activities. Therefore, we need to predict to ensure synchronization.

All these socializing behaviors like our synchronization with predictions and observations foster implicit learning (IL). As for the relationship between SI and IL, they go hand in hand. SIs provide opportunities to learn from the behavior of others. For example, the best way to learn ride a bike is to watch someone ride a bike and learn implicit motor skills such as how to coordinate hand and foot, as well as to plan movements based on external factors such as sloping road or other disturbances on the field. In this learning process, we learn how to ride and how to adapt or avoid disturbances without awareness. Here, we learn implicitly not only by watching or interacting socially with someone, but also with the help of haptic interaction.

The term “haptic” refers to the mental activities of the sense of touch, which provides the interaction of the human with the outside world, and the proprioceptive sense, which allows the perception of joint movements and positions in space [1-2]. We often use haptic interaction (HI) without realizing it in the implicit learning process.

1.1 Motivation

Human SIs are significantly more intricate and satisfying because of giving us a sense of connection, direction, aim and support as well as, eventually, improved health and longer life [3]. For this reason, it is also difficult to understand human social interaction, its effects and results on our behaviors. Although there are many studies on SI, it remains always being hot topic.

The main motivation of this study is understanding human social interaction by using human-animation interaction system to evaluate synchronization, prediction and implicit learning with haptic interaction and to find answers to questions such as how haptic interaction affects IL process, what is the relationship of implicit learning with synchronization and SI, how changes in HI affect implicit memory (IM).

1.2 Scope of Thesis

This study is to provide an overview of how haptic interaction (HI) affects implicit memory. Assistive HI (AHI or HI+), resistive HI (RHI or HI-) and setup without HI were used to understand the changes in performance of IM. According to our hypothesis, HI- affects implicit memory positively. To validate the hypothesis, various metrics and statistics (ANOVA) are used.

This thesis includes studies in the literature on social interaction, synchronization, prediction, implicit learning and memory and haptic interaction; experimental setup and procedure developed to confirm the hypothesis that haptic interaction positively affects implicit memory; experimental results and interpretations.

1.3 Contribution of Thesis

The main ambition of this thesis is to show the improvement in IM when the subject is exposed to resistive haptic interaction. Implicit learning and implicit memory with HI studies generally use Serial Reaction Time (SRT) tasks which Nissen and Bullemer introduced [4]. On the other hand, experimental setup used in this thesis was established with Dynamic System Control (DSC) task. Therefore, this thesis makes a contribution to the literature by constructing a different experimental setup.

In literature, metrics for the IL and IM are limited. It is obvious that the thesis contributes to the literature in terms of demonstrating performance by using a large number of metrics and using statistical analysis methods.

Although there are studies in the literature on implicit learning and haptic interaction, this thesis adds a novelty as it is a study in which IM or skill transfer and haptic interaction are studied together.

CHAPTER 2

LITERATURE REVIEW

The "social brain theory" [5,6] states that some regions of the human neo-cortex have evolved to enhance survival in dynamic groups and, consequently, to interpret social information. This makes it possible for humans to effectively mate, being parent, establish connections, connect with, and comprehend one another [7]. SIs play a significant role in the formation of society and in one's own psychological health.

There are two theories for the model of SI in literature. One of them is the field theory which consists of doctrine of interactionism introduced by Snow [8] and doctrine of reciprocal determinism put forward by Bandura [9]. Another theory for the SI model is the general social interaction cycle (GSIC). According to doctrine of interactionism, behavior is a function of factors internal to the person and factors in the external environment. A person and situation are independent factors, and they create behaviors.

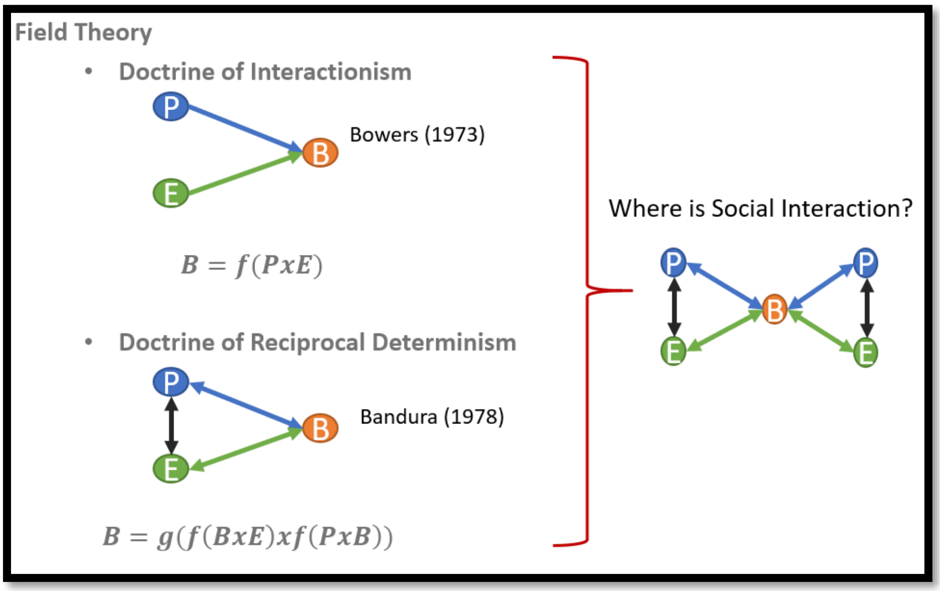


Fig. 2.1. SI according to field theory

As for doctrine of reciprocal determinism, it states that while function of behavior and environment creates person, environment is a function of behavior and person.

There is triadic reciprocity, so that all components affect each other. Therefore, SI can be modelled as when two individual creates behaviors as a result of internal factors of person and external factors of environment as illustrated in Fig. 2.1.

GSIC describes the dyadic social interaction, and it can be generalized. There are two main roles which can be called actor and target. The actor initiates interaction and target's assigned role is object of actor’s action. Target responds to actor and actor interprets the response. Roles are arbitrary and this is how this cycle works [10, Fig. 2.2]. Illustration of GSIC is given in Fig. 2.2.

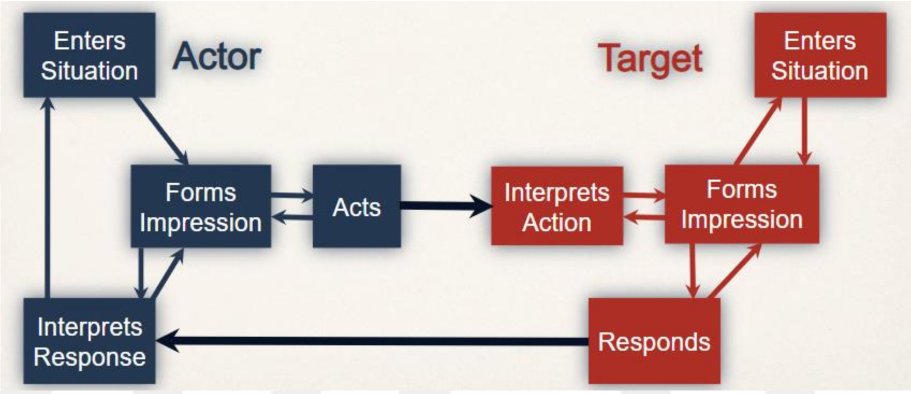


Fig. 2.2. General Social Interaction Cycle (GSIC) [10].

When body movements and vocalizations, or both of them synchronized, we can interact with others. SI also takes place by observing and understanding the feelings and movements of the other person. Observing someone else in a certain emotional state like pain [11-12], pleasure [13], and disgust [14] immediately and automatically causes the observer to exhibit the same behavioral, physiological symptoms and brain activities in terms of neuroimaging studies as the other person [15]. Observing and sharing others’ emotional and behavioral states are possible to adapt, mirroring an interaction partner’s behaviors and synchronize [16-17].

Being in sync is not just defined by synchronization with someone or someone's emotions. We even synchronize with our own body naturally when breathing, controlling our body. Synchronization, which is an inevitable feature of us, has also been the subject of many studies. There are many examples of human-human synchronization experiments such as leader-follower (LF) [18] or mirror game (MG) tasks [19-20] and human-computer synchronization experiments like virtual player

(VP) tasks [21]. One of the experimental studies for MG, with or without a chosen leader, it is created an attractive and synchronous task that is given in Fig. 3.

Fig. 2.3. Experimental setup for MG [22]

In the collective improvisation of motion, they seek to answer the issue of how uniqueness and unity interact. When players take on leadership roles, they exhibit unique motion characteristics. As a result, the fundamental movements of every player create a unique signature that takes up a certain place in shape space. The segment shapes of players that improvise in concert in co-confident motion, which is synchronized motion without a clear leader or follower, are limited to a finite and universal region of the shape space [22, Fig. 2.3].

Another study which uses MG paradigm as well presents that players produce intricate and tightly synchronized motion together and experts perform better without a designated leader [23]. One dimensional experimental setup for MG consists of two parallel tracks and handles on these tracks. Players can move this handles right and left by holding them. Then, two rounds announced to players which are JI, without a leader players try to move handles togethers and LF, one player took the initiative, and the other followed.

In the age of evolving technology and automation, human-computer synchronization studies have not been able to escape being one of the most researched topics. Virtual player experiments are the best way to investigate human-computer synchronization given the scope of our study. Some mirror game experiments consist of virtual players, and they are conducted between VP and HP in literature. To create the virtual player, they develop a control law to act like a human player and track or lead to the human player [21]. All these synchronization experiment like LP, VP, MG require prediction of players to perform the task well. Improved interaction performance is the outcome of better peer anticipation of impending actions. Dancers, musicians, basketball players etc. predict the acts of their partners or teammates for synchronization and interaction.

2.1 Explicit and Implicit Learning

Recently, consciousness in human learning processes has been a highly researched topic. These studies have led to the emergence of two concepts in literature: explicit learning (EL) and implicit learning (IL). Starting with the definition of EL, it is considered to be knowledge of motion behavior created verbally. It incorporates cognitive learning phases and therefore is based on working memory participation. The definition suggests that during the learning process, the learner is aware of all the fundamental principles and guidelines governing the motor skill that has to be acquired. Verbal specific instructions are regularly employed in practice and frequently help patients to be conscious of their own bodily motions. [24] Implicit motor learning advances unconsciously and with little to no growth in verbal understanding of movement performance (such as facts and standards). It is argued that learning happens less consciously and more spontaneously. People are aware of the learning process while they are unable to recollect the fundamental knowledge and rules governing motor skill [24]. As mentioned before, implicit learning is fed from synchronization and prediction and it is inevitable if a person's tracking ability, synchronization, and the performance of their predictions to support this synchronization are good. We use many actions for implicit learning to occur. Listening, observing and imitating are some of them. As a result of this relation, IL has a direct effect on the SI.

While conducting IL research, some experimental studies have been carried out for the characteristic of IL such as learning a complex rule was studied in [25], covariations learning from [26], probability learning by [27] and learning complex rule system [28] as in [29]. The learnt rule system is complicated and challenging to learn consciously, which is one of the most significant shared traits that these research emphasizes. This can also be expressed as the intricacy of the rule system and perceptual discrimination are two essential attributes of implicit learning.

Not only rule system and perceptual discrimination, but also robustness, age and IQ independence, low variability and commonality are the important characteristics found in literature [30]. Robustness of IL described as given that they originated earlier on the evolutionary history than conscious processes, unconscious processes should be strong when it comes to disorders. For age and IQ independence, compared to EL, IL is essentially independent of both age and IQ. In different species, it is observed that IL process ought to highlight the similarities while the degree to which may acquire implicit information varies quite little in the same species [30].

There are many experimental studies on implicit learning in literature. Implicit learning experiments are conducted to test whether learning hypothesis for explicit learning are also valid for implicit learning [31-34], capability of implicit learning for different age group [35] and for people suffering from stroke and other diseases [36-38] and also to investigate the influence of contextual cues [39]. To test transfer and retention of implicit learning [29], to test the implicit memory [40], even tracking capability of monkeys was tested [39].

2.2 Paradigms for Implicit Learning

When conducting these experimental studies some tasks and paradigms should be used to carry out these studies. Serial Reaction Time (SRT) [4, 41], Artificial Grammar Learning (AGL) [42-43], Learning of Conditional Responses (LCR) [44], Acquisition of Invariant Characteristics (AIC) [45], Perceptual Learning Paradigm (PLP) [46], Learning of Perceptual Categories (LPC) [47], and Second-Language Acquisition (SLA) [48-49], Probability Learning (PL) [50] and Dynamic System Control (DSC) [51] paradigms are used paradigms for examining IL and IM systems [52]. On the other hand, most commonly used tasks are SRT, AGL and DSC in literature.

SRT tasks are used wherein participants are required to regularly react to a predetermined sequence of cues, each of which denotes the necessity for a certain response such as pressing a button or tapping. The probabilities governing the clues appearing in a repeated sequence and in a random order are beyond the participant's knowledge [53]. For this reason, predictability emerges that affects the reaction time of the responses resulting from the cues. When a result, as participants learn and use these transition probabilities, reaction times to these cues go faster and faster. As for how SRT is used in IL applications, changes in participant's response time are measured by giving 10 hidden and consecutive clues in a sequence. Improvements in performance reveal the existence of implicit learning, as participants are unaware of these sequencing. Because if the participant unconsciously learned that pattern, improvements in performance and reaction time occur. In Fig. 2.4, an example for SRT task is given. According to this task, four visual cues are placed horizontally on computer screen and when they appear, expected thing from the participants is that correspond to one of the 4 buttons set according to the 4 visual cues in front of it and whenever participants respond trial ends [53, Fig. 2.4]. Response time of participants are measured. After a fixed delay at the end of each trial, the next cue comes. After these sequential trials, repeating sequences of visual cues begin. Participants begin to predict and learn implicitly.

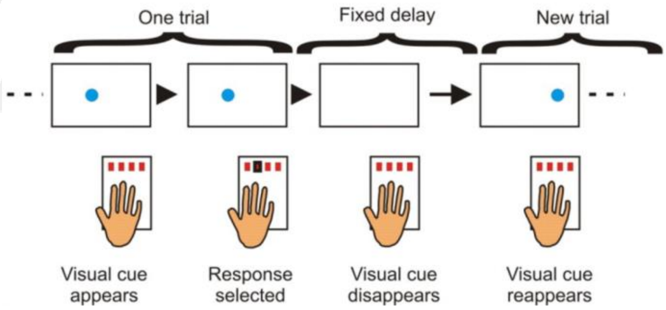


Fig. 2.4. SRT task example [53]

Research on AGL often has two stages. Examining a group of letters which obey all rules of artificial grammar is expected from the participants. As the second stage, students should separate the newer series if they are obeying the grammar rules or not. In the studies of learning artificial grammar, results generally show that students separate the series better than the probability does. Although, when the reason of choosing that series was asked by the students, they could not explain the thinking behind the choice by words [54].

In Humphreys' experiment, who created the first PL paradigm experiment, the participant was given a ready signal, instructed to foretell whether or not a reinforcing event would occur, and the outcome was then recorded [51]. This experiment was similar to a conditioning experiment since it allowed for reinforcement to be evaluated while using the findings to support each participant's expectations. Later, this experiment was modified in a significant way in terms of adding additional buttons that represented different outcomes participants had to predict instead of one button which was insufficient. The findings revealed that people's replies matched the likelihood of the outcomes. PL demonstrates the IL of a random patterns in an event sequence [51].

The paradigm designed by the participants trying to control the outcome variables by providing control over the input variables is called the DSC paradigm. Throughout the experiment, participants are aware of the outcome variables and are allowed to alter the input variables as desired. In experiments using this paradigm, participants can somehow manage to control the system, but they cannot verbalize the rules and system they use to control the system. Because the learning process takes place implicitly.

One of the best examples of DSC paradigm being used is sugar production experiment by Berry [51]. According to the experiment, participants were invited to assume the position of manager of a factory that produces sugar. The main purpose of the manager is producing a specific amount of sugar output as a result. Participants were asked to alter the value for the number of factory workers which is input to produce sugar in order to get the ideal level of sugar output. Moreover, another example of DSC task using experiment also conducted by Berry and Broadbent which is called person interaction task. In this task, there are two players which are participant and virtual player as VP tasks in many MG studies. The computer-person is designed to interact at a predetermined level of closeness. The person must engage with the computer and adjust the closeness level until it is set to "extremely friendly." The "extremely friendly" level had to be maintained by participants [51].

2.3 Experimental Studies for IL

Pew used Continuous Tracking Task (CTT) paradigm to investigate implicit motor learning (IML). The capacity of a person for prolonged and focused attention can be tested by using neuropsychological tests called CTT. The CTT's fundamental tenet is that participants must follow a target while using a hand-operated device to track [55, Fig. 2.5]. Moreover, in tests, the target moves along an invisible course made up of, typically, three parts that are random, repeating, and random as shown in Fig. 5. The trajectory of the target consists of superposition of sine and cosine waves with certain set of parameters.

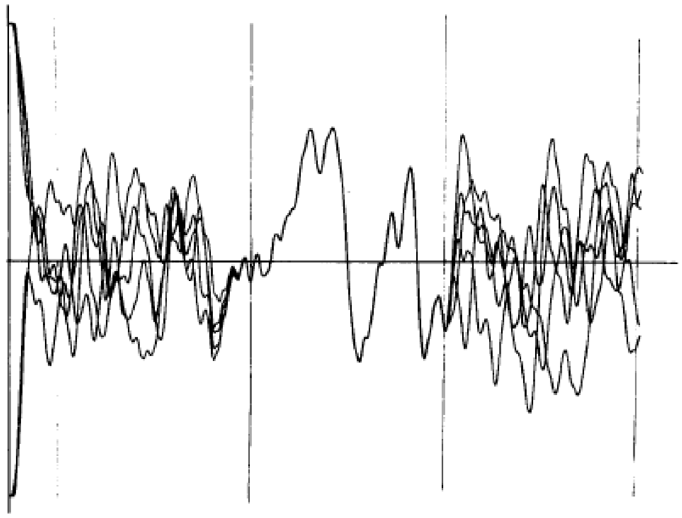


Fig. 2.5. Generated waveform including random-repeated-random segments for CTT paradigm by Pew [55]

Participants try to track the generated waveform given Fig. 2.5, then it is observed that there was an improvement in performance of middle segment which was not randomly generated. After the success seen in mid-section performance, some manipulation was used to evaluate the nature of the information stored about the repeated segment [55]. For example, while all the aspects of trials are the same, repeated segments were precisely inverted at the end of day 11 as a manipulation. So that, while subject must move the left before, they should move the right now. Many subjects lowered their performance in the middle segment. Therefore, we can say the following for the output of this study, if automation or over-learning has taken place, tracking performance decreases as less attention and processing capacity is required.

Wulf and Schmidt [34] also used the Pew's continuous tracking performance paradigm to examine the variable and constant practice effect and their comparison on IL. So that, there are some changes in pattern which participants follow. These changes are related with the amplitude of the trajectory and the durations of segments. Experiments are planned to be constant amplitude of trajectory will be given to the subjects while same subjects participate variable amplitude of trajectory [34, Fig. 2.6]. As for duration of segments, a mechanism was designed in which the subjects were tested by starting the repeated segment early or ending it late, manipulating the time and keeping it constant as given in Fig. 2.6. As a result of this research, they observed that groups exposed to variable practice have more effective transfer performance when it is compared with the constant practice group.

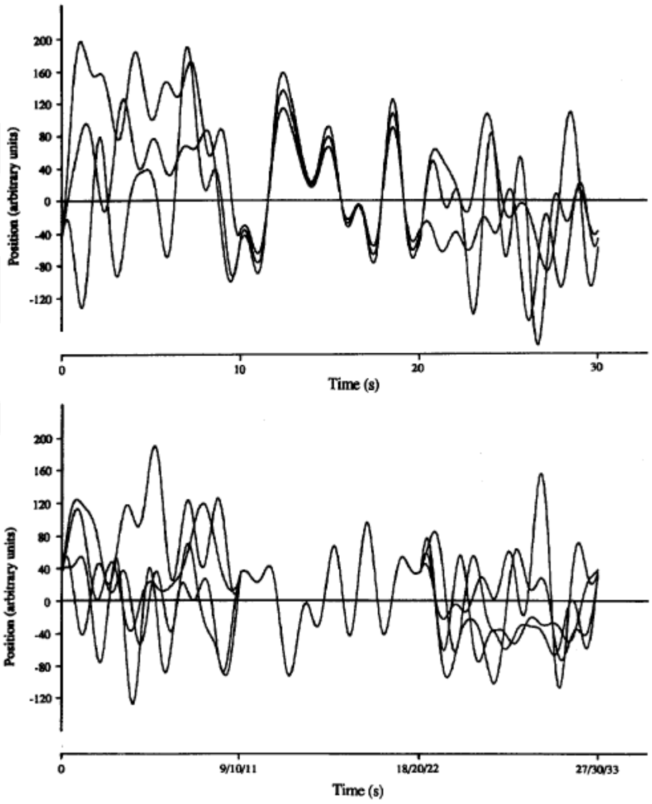


Fig. 2.6. Trajectories for continuous tracking tasks with amplitude-manipulated (top) and time-manipulated (bottom) used in [34].

Chambaron et al. [56] shared most of the common features with [55] and [34]. They had two experiments with similar tracking tasks. These two experiments differ in terms of duration of the experiment. While the duration was 36 seconds in the first experiment, it was shortened to 15 seconds to see the increase in difficulty of tracking. One of the difference from the other experiments in literature about the continuous tracking paradigms, they used a different repeated segment for each participants [56]. Therefore, the characteristic of middle segment, which is repeated, and characteristic of random segment modulate their difficulty level during the whole experiments. Then, they repeated the same experiment, but now standard repeated segment which is in used [55] were used. All other procedures were the same as in their first experiment. As a result of these experiments, they concluded that shortening the experiment length is more challenging and that the difference between the segments is much greater when the conventional repeated segment is used. They used two given metrics which are integrated absolute error (IAE) and root mean square error (RMSE) to validate experimental results and comment on it.

$$f_{IAE} = \int_0^t |e(t)| \, \mathrm{dt} \tag{1}$$

where e denotes the tracking error between target position and participant position, t is the duration of the experiment.

$$RMSE = \sqrt{\sum_{k=1}^{n} \frac{(x_k - \hat{x}_k)^2}{n}} \tag{2}$$

where n is sample steps number throughout the simulation, and $x_{1,k}$ and $x_{2,k}$ refer for target and participants' positions.

According to [32], Sekiya et al. employed a similar tracking paradigm, but his four experimental groups were produced by combining two implicit and explicit awareness conditions with two blocked and serial practice-order conditions. Explicit-blocked and explicit-serial groups are informed that there were four experiments and two specific patterns out of four segments. On the other hand, segmentation and specific patterns are kept secret from the implicit-blocked and implicit-serial groups. There was not much difference between the explicit and implicit groups, although there was an expectation that the explicit group would perform better on the repeated segment [32]. The metric they use to measure and compare performance, unlike the others, is mean radial error (MRE) which can be calculated as given in equation (3).

$$\mathrm{MRE} = \frac{\sum_{i=0}^{n} \sqrt{(TXt - PXt)^2 + (TYt - PYt)^2}}{n} \tag{3}$$

where TXt is target horizontal displacement at moment t, PXt is horizontal displacement of participants at moment t, TYt is target vertical displacement at moment t and PYt is vertical displacement of participants at moment t. Number of data points for each segment is denoted as n.

In one of the studies that used the continuous tracking performance tasks to clearly demonstrate the presence of IL, two separate experiments were performed in which 3 of the 3 segments were random and the middle segment was repeated instead of the random segment, and the results were as expected [32].

Kunzell et al. [57] conduct experiment by changing the target speed to see how changes occur in performance of participants. A strong Speed x Segment interaction was also seen in the first and final test conditions, which are equivalent to the practice condition [57]. No significant differences were found between the three segments in the slow condition, while the repeated segment means in the medium and rapid conditions both dropped outside the bounds of the random segment's confidence intervals.

While the character and existence of IL continues to be the subject of many studies, the transfer and retention of IL has also begun to take its place among the subjects studied. In some articles, this is referred to as skill transfer, while some researchers work on IM by associating IM with the transfer of IL. All these studies are actually about the robustness of implicit learning. When it is compared with explicit memory, resistance to memory deficits and robustness of IM are better. Because numerous research has demonstrated that, compared to explicit memory, implicit memory is more resistive to cognitive and psychiatric disorders.

In [29], they try to examine the characteristics of IL and EL in terms of robustness. They used a multiple-choice questionnaire about the experiment content to measure the explicit knowledge (EK) of subject while they measure the difference between performances of subjects for the implicit knowledge (IK). Given that these two assessments evaluate precisely the same characteristics of the stimulus structure, if individuals have IK of the task, their measure of task performance should be higher than the measure of their EK. There were 2 tasks which has simple rules for EL that consist of 2 simple equations with input multiplied by coefficient and output and complex rule for IL that consist of 2 difficult equation with that 2 inputs multiplied by different coefficients and sum or subtract of them creates the output.

Transfer effects of the complex and simple tasks were examined by the experiment [29]. Learning a new complicated task with different rules after learning the one must be more challenging if, as claimed, it is more difficult to change IK than to change EK. In other words, learning a new complicated task should be more negatively impacted by their prior experience with a complex task than learning a new simple job should be impacted by their prior experience with a simple task. So, they divided the subjects into 4 groups as below:

1. The complex task with experience of other different complex task
2. The simple task with the experience of other different simple task
3. The complex task without other experience of learning task
4. The simple task without other experience of learning task

Later, subjects were given guidelines about whether there were certain patterns and how to complete the task. To complete the tasks, they must find the correct inputs through the outputs that match them as the DSC task. As a result of this experiment, subjects were able to adapt to new rules or tasks and even benefited from learned old rule for EK, while formerly learned IK made it challenging to learn a new rule or task. Because subjects are aware of the learning and what have learned in EL and this made it easy to modify learning conditions. The unconscious learning feature, which is the most important feature of IL, actually makes it difficult to learn a new implicit learning task because old acquisitions have an effect on the subject's new acquisitions [29].

The retention or durability of EL and IL are also examined in [29] by retesting participants after they learn the simple and complex task. Although they conducted a pilot study by retesting participants one day after they were exposed to simple and complex tasks, it was extended to one week because there was no change in the subjects’ performance. During the retesting, no subject was informed of the reason for the return, and they were not tested with learning tasks. Performance tasks and questionnaire as in the first test should be performed. While retesting gives negative result of EL, there was no decline in performance tasks and questionnaire of IL. Thus, it was proven that IK is more robust and durable than EK. Freud [58] described the way of altering IK as “making the unconscious accessible to consciousness”.

When using paradigms such as SRT and DSC to explore implicit learning, we unconsciously find ourselves in haptic interaction. Many participants benefit from haptic cues or improve their performance with the multiplicity of haptic interactions. These haptic interactions can be assistive as well as resistive. As a matter of fact, we are mistaken in believing that the HI+ will improve performance as we modify the experimental setting such that participants are forced to reveal IM rather than acting as they would typically expect them to.

There are some studies advocating that haptic guidance (HG) negatively affects motor learning. Although HG is good for task performance and its positive impacts can be seen in many examples, motivation of participant and effort on the task performance decreases when HG is applied. HI+ may cause limiting the somatosensory information necessary for motor learning by interfering with the sense of the motion of the environment [59]. In other words, limiting motor variability, which was crucial for IL, also limits motor gains and learning. Model Predictive Controllers (MPC) were used in [60, Fig. 2.7] to reduce the assistive forces in order to encourage the increase in movement variability. Using the environment's dynamical model to forecast the system's future states and reduce aiding forces is defined as MPC by [61].

Fig. 2.7. Experimental setup called Delta 3 robot for [60]

They use two MPCs in the experiments which are acquired from participants to hit the pendulum ball target during a virtual pendulum swings. One of the MPC used in experiment which is shown in Fig. 2.7 called end-effector MPC and it is used to apply optimal HG directly on robot. Moreover, another MPC which is called as ball MPC applies its forces on the virtual pendulum ball. Pendulum dynamics are directly affected by the ball MPC, so that its effect of human-robot interaction forces gets smaller. Therefore, task performance and motor variability of subjects increases gradually while performance variability decreases in training with used MPCs.

In another study arguing that motor learning is facilitated by disturbance forces, 3 different experiment conditions which are robot haptic assistance, robot haptic disturbance and no haptic guidance or disturbance are created. Active inference driven by surprise is suggested by Free Energy Principle (FEP) [62]. According to FEP, minimizing free energy and reducing the entropy as ‘Shannon’ information theory perspective [63] driven by biological systems. Predictions about the environment are taken as an active inference machine by the brain. Better predictions about the environment indicate lower entropy and free energy [63].

CHAPTER 3

MATERIALS AND METHODS

We always resort to experiments, research or numerical data to defend hypotheses and claims as seen in the literature review. The experimental setup and the hypothesis must be in harmony with each other. Otherwise, the experiment outputs received may have no meaning. Therefore, by examining the experiments and studies in the literature, I tried to design the most appropriate mechanism to confirm my hypothesis. In this chapter, the design of simulation and the experimental setup, the participants, the experimental procedure, experiment configurations to verify the hypothesis are explained.

3.1 Simulation

To develop the human-animation interaction system, MATLAB/Simulink were used as software. Moreover, Simulink Desktop Real Time which allows users to run their simulations as in the real time with kernel that your operating system prioritizes as high as possible. Human-animation interaction system simulation consists of mathematical model of double-mass-spring damper system, position controller for mass, reference trajectory, VRML part for animation. Moreover, a data collection tool will be mentioned under this heading.

3.1.1 Double Mass-Spring-Damper System (DMSDS)

The reason why the double mass spring damper system shown in Fig. 3.1 was chosen within the scope of this thesis is that we have a good command of its dynamics. Moreover, it provides us freedoms regarding the model since we can easily express its movements mathematically and it is an underactuated system.

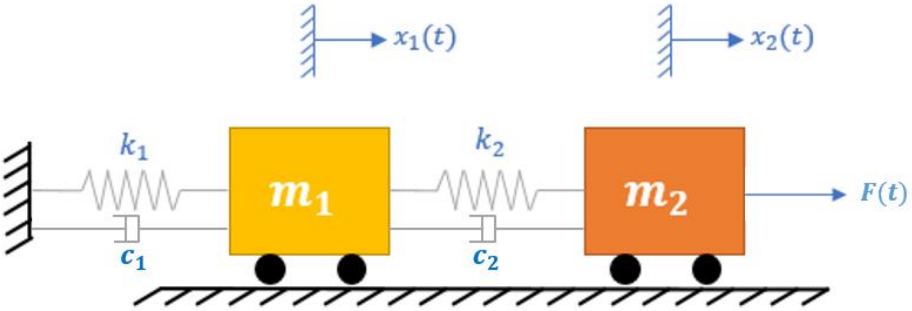


Fig. 3.1. Illustration of Double Mass-Spring-Damper System

This system is used in many different areas like robot manipulators and suspension systems of a vehicle, and it is a traditional model for mechanical engineering. A mathematical model for double mass-spring-damper system is given below.

Since DMSDS has 2 degree of freedom, 2 equation is needed to establish the mathematical model. One equation is coming from the mass 1 by writing the forces acting on it as in the followings. Fig. 3.2 shows the FBD of mass 1.

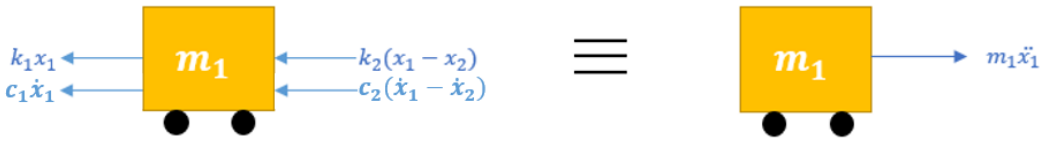


Fig. 3.2. Illustration of FBD of Mass 1

According to Newton's second law of motion [64], when all acting forces are not balanced, object will accelerate based on the net force acting on it and mass of object as given in equation (4).

$$\overrightarrow{F_x}^{+} = m_1 a_x \tag{4}$$

$$-k_1x_1 - k_2(x_1 - x_2) - c_1\dot{x}_1 - c_2(\dot{x}_1 - \dot{x}_2) = m_1\ddot{x}_1 \tag{5}$$

$$\ddot{x}_1 + \frac{(c_1+c_2)}{m_1}\dot{x}_1 - \frac{c_2}{m_1}\dot{x}_2 + \frac{(k_1+k_2)}{m_1}x_1 - \frac{k_2}{m_1}x_2 = 0 \tag{6}$$

As for equation of motion of mass 2, there is FBD of mass 2 given in Fig. 3.3. The equations were written by providing force equality as in mass 1.

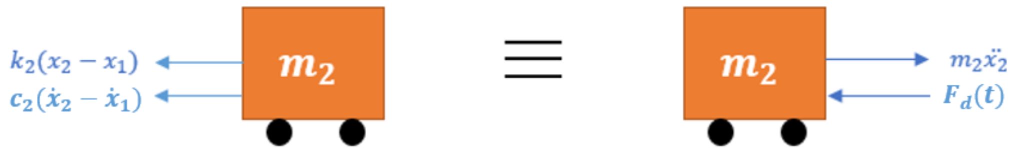


Fig. 3.3. Illustration of FBD of Mass 2

In Fig. 3.3, forces acting on the mass 2 are illustrated where $F_d(t)$ represent the disturbance forces through the x-axis.

$$\overrightarrow{F_x}^{+}=m_2a_x \tag{7}$$

$$-k_2(x_2-x_1)-c_2(\dot{x}_2-\dot{x}_1)-F_d(t)=m_2\ddot{x}_2 \tag{8}$$

$$\ddot{x}_2+\frac{(\dot{x}_2-\dot{x}_1)}{m_2}c_2+\frac{(x_2-x_1)}{m_2}k_2+\frac{F_d(t)}{m_2}=0 \tag{9}$$

After equations of motion are derived for DMSDS, it should be modelled in simulation environment which is Simulink. The block diagram for these two equations (6) and (9) was created as shown in Fig. 3.4 and Fig. 3.5.

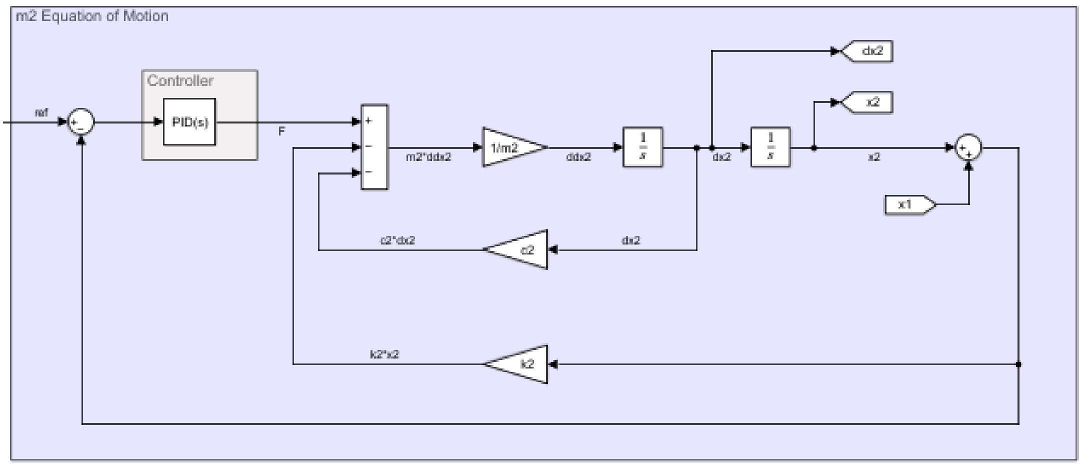


Fig. 3.4. Simulink block diagram for mass 2

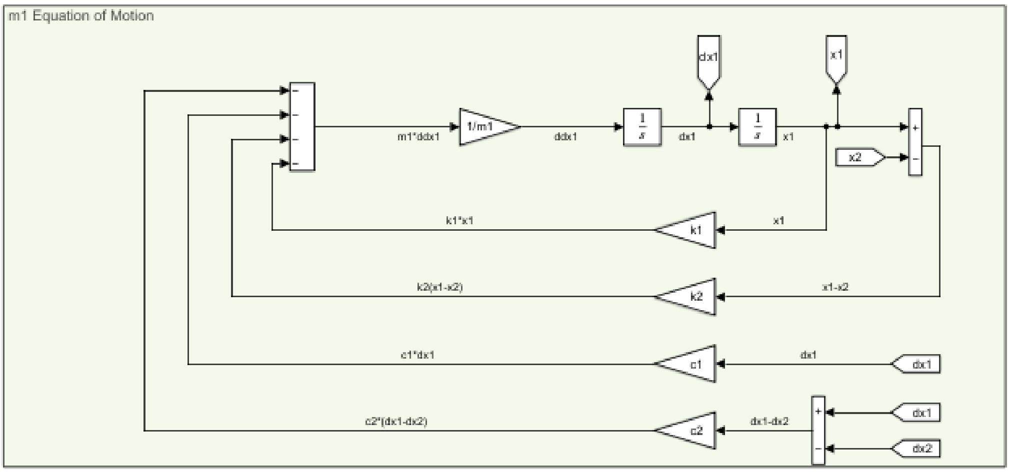


Fig. 3.5. Simulink block diagram for mass 1

3.1.2 Position Controller

To control the position of the mass 2, a proportional integral derivative-based controller was used. The position of mass 1 is assumed as disturbance force acting on mass 2. PID controller was used for the reference tracking of mass 2. The controller was implemented to the Simulink diagram as Fig. 3.6. PID Tuner app which is the application of Simulink was used to tune the gains of controller.

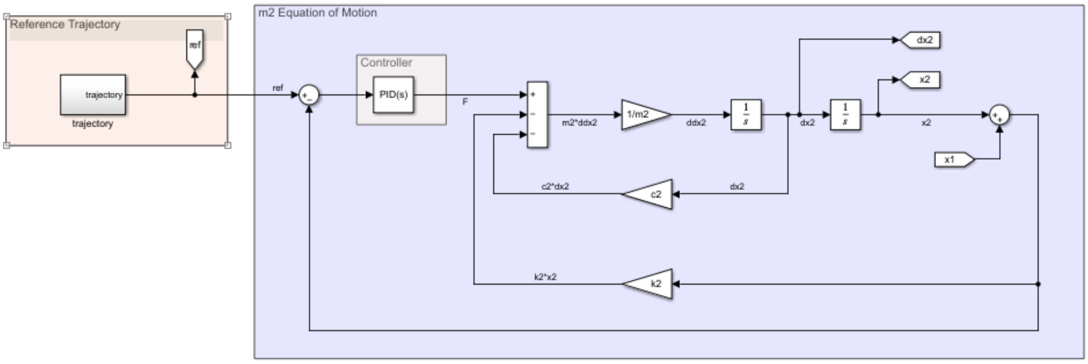


Fig. 3.6. PID controller for position control of mass 2 in Simulink

3.1.3 Reference Trajectory

Reference Trajectory was modelled with superposition of sine and cosine waves with certain set of parameters as [55]. Below function is used to generate the reference trajectory.

$$f(x)=b_0+a_1\sin(x)+b_1\cos(x)+a_2\sin(2x)+b_2\cos(2x)+a_3\sin(3x)+b_3\cos(3x)$$
$$+a_4\sin(4x)+b_4\cos(4x)+a_5\sin(5x)+b_5\cos(5x)+a_6\sin(6x)+b_6\cos(6x) \quad (10)$$

where b_0, a_1, b_1, a_2, b_2, a_3, b_3, a_4, b_4, a_5, b_5, a_6 and b_6 are randomly selected between -25 and 25 for random segments which are between 0-10 seconds and 20-30 seconds to create different trajectories for every trial. On the other hand, they are selected as b_0=0.6206, a_1=1.9480, b_1=-0.7354, a_2=3.3627, b_2=2.3139, a_3=-1.3997, b_3=-0.4579, a_4=-1.1361, b_4=2.7555, a_5=2.3427, b_5=-0.6972, a_6=1.9375 and b_6=4.4521 for repeated segment which placed between 10 and 20th second of the simulation. Therefore, the middle of the simulation was designed as the same for every trial of subjects to see IL existence for repeated segment. Simulink diagram of reference trajectory is given in Fig. 3.7.

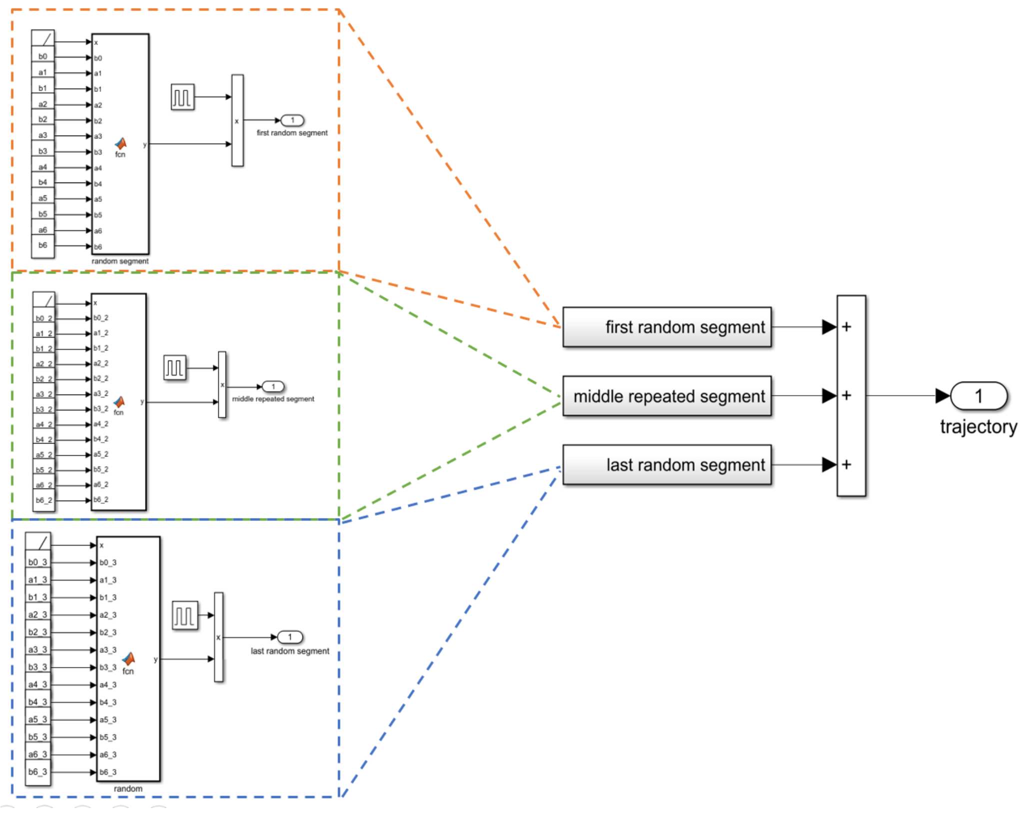


Fig. 3.7. Reference Trajectory as random-repeated-random in Simulink

Function variables are given from the MATLAB workspace as random for segment 1&3 and constant for segment 2. Constant variables are chosen between -5 and 5. The sum of the functions as shown Fig. 3.7 gives the 30 second trajectory.

3.1.4 Animation

Virtual Reality Modeling Language (VRML) in MATLAB was used to create animation which provides subjects to visual synchronization tasks. No spring modeling was done so that the compression and loosening of the spring is not visually confusing. Masses and the rail on which the masses move was simulated. Position data from the mathematical model in the Simulink was fed to the masses in animation. In addition to these, a ball-shaped avatar has been added to the animation so that subjects can watch their own synchronization. Finally, the cumulative score of the subjects was written on the animation. Therefore, they could observe their own performance while trying to complete the task.

3.1.5 Apparatus for Experiment and Data Collection

To accompany the animation and move the ball-shaped avatar for synchronization, Logitech driving force GT was used. It is a steering wheel shaped joystick that has force-feedback feature, and it can work in real time. Simulink desktop real time analog input block was used to take data from the subject. Just the opposite, analog output block was used to haptic guidance or disturbance. Moreover, joystick parameters are adjusted as having stiffness %15 and damping %15. Centering feature is enabled when subject does not apply force to joystick. Simulated VRML environment and Logitech steering wheel shaped joystick connected to the PC which was used in experiments are given in Fig. 3.8.

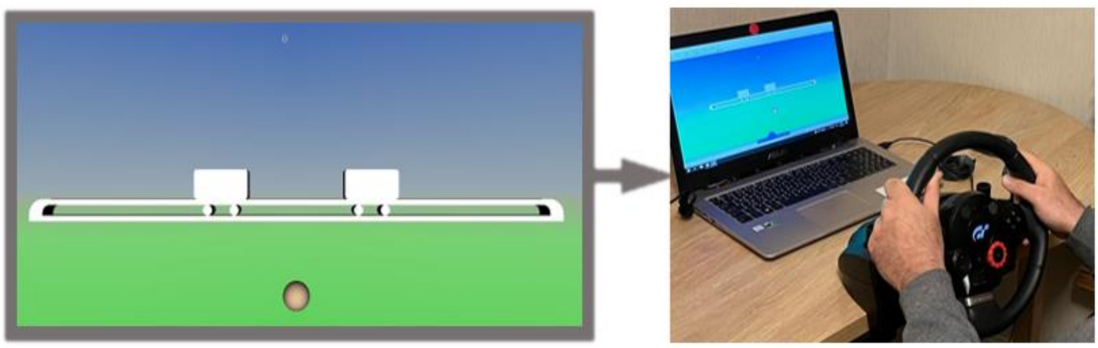


Fig. 3.8. Designed animation screen (left) and joystick used in experiments (right)

3.2 Participants

Experiments were conducted with 30 subjects aged between 18 and 35. They all had vision that was normal or corrected to normal. The experiment's goal was kept private from the participants, and they had no prior training in the activity. The subjects were told to accompany and follow the animation they saw. Subjects were informed that ball-shaped avatar represented their position.

3.3 Experiments

Three different experimental setups were designed to observe how haptic interaction affects IL and the transfer and persistence of IL. The subjects were divided into 3 different groups, each of 10, to participate in only one of the 3 experimental setups. In other chapters of the thesis, these experimental setups will be named as follows:

- Experiment 1 : No HI+ or HI-
- Experiment 2 : Haptic Guidance (HI+)
- Experiment 3 : Haptic Disturbance (HI-)

Data will be collected using experiment 1 procedure to demonstrate the existence of IL and it will be proven according to the improvement of performance in the repetitive segment by using metrics and ANOVA.

To test the transfer of the IL in different haptic conditions, all experiments will be conducted using similar procedures but only one difference that after learning phase is over, trajectory will change as random-random-repeated instead of random-repeated-random segments. If the subject can also show improved performance in the previously middle segment when the repeated segment is relocated, this will show us how the transfer of implicit learning is affected when the haptic conditions are changed. If the subject fails this experiment, it will show that IL is more difficult to transfer or how it changes in haptic situations. Lee [29] suggests that it is difficult to learn new IL tasks due to robustness characteristics of IL and unconscious learning property of IL.

As for durability of the IL, subjects will be retested with the same experiments 1 day and 1 week after participating in all experiments. After 1 day and 1 week, the change in their performance will be observed and we will be able to comment on how permanently they learned in which experiment. That is, data will be taken from the same subjects, 3 times as first exposure of the experiment, one day and one week later from the first with the same procedures.

3.4 Experiments Procedures

Experiment 1, 2 and 3 were conducted with the same procedures to distinguish the differences in transfer and retention of the IL. Experiment procedures which were followed for 3 groups of subjects are as follows:

- Subjects participated in experiments with phases which are training, learning and test phases.
- The training phase consists of 2 trial and no data will be saved during this phase.
- The learning phase consists of 10 trial, and it is expected that the subject will learn the task in this phase and his/her IL performance was expected to improve from trial to trial.
- The test phase consists of 2 trial which were conducted with trajectory of learning phase (random-repeated-random) and changed trajectory for testing transfer of IL (random-random-repeated).
- Each trial takes 30 seconds and random parts of trajectory were changed in every trial.
- Repeated segment is between 10 and 20th seconds for learning phase trajectory while changed trajectory for testing transfer of IL include repeated segment between 20 and 30th seconds. The existence of a repeating segment was also not disclosed to subjects.
- The subjects were told to accompany and follow the animation they saw. A round that simulates the subject's position and cumulative score of subject has been added to the animation to track their performances.

CHAPTER 4

METRICS AND STATISTICAL ANALYSIS

In order to make the collected data meaningful, some metrics and performance criteria need to be determined. Since datum consist of position of the subject and positions of the reference masses, root mean square error of the position, circular variance from the position, entropy and similarity level of the subject were defined as metrics. Moreover, velocity of the subject and masses were founded by using position data and Butterworth lowpass filter. Due to filtering, data can be noise-free. By using velocity data, EMD was defined as metric. In addition to the defined metrics, kurtosis and skewness of subject and masses were calculated for every trial. According to kurtosis and skewness, overlaps were defined as well. Then, first-way ANOVA analysis done according to RMSE, entropy, CV, EMD.

4.1 Root Mean Square Error (RMSE)

The position error between the subject and masses was found. It is also called as position temporal correspondence in tracking tasks [65,66] and root mean square error calculated as root of summation of the squares errors mean as given below:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(x_{m,k} - x_{s,k})^2} \quad (11)$$

where n is the sample number throughout the simulation, and $x_{m,k}$ and $x_{s,k}$ are the mass and subject positions respectively. Low RMSE indicates good follow-up performance and improved IL.

4.2 Circular Variance (CV)

The performance of the subject in tracking tasks were measured by circular variance (CV) as well. It is formulated in literature as follows [66,67]:

$$CV = \left\| \frac{1}{n} \sum_{j=1}^{n} \exp\left(i\Delta\phi_j\right) \right\| \quad \in [0,1] \tag{12}$$

where n is the number of the time steps and $\Delta\phi_j$ represents the relative phase between the subject and target mass. A high circular variance metric indicates good tracking performance and synchronization.

4.3 The Earth Mover's Distance (EMD)

As mentioned before, noise-free velocity of the subject and mass was found by using the position datum. Cumulative distributions of the velocity profiles was found and EMD was calculated by using them. It gives us information about individual motion signature of the subject and mass. Smaller EMD shows that performance has improved, it is calculated as given below [65, 68-70]:

$$EMD = \int_z |CDV_m(z) - CDV_s(z)|\, dz \tag{13}$$

where cumulative distributions of velocities are represented as CDV_m for mass and CDV_s for subject.

4.4 Shannon Entropy (SE)

The average degree of random variables' uncertainty is represented by Shannon Entropy which was defined as metric for performance of subjects [71] and it is calculated as given below:

$$SE = -\sum p(n) \log_2 p(n) \tag{14}$$

where p(n) is the possibility that the event n will occur. The fact that the entropy is low indicates that the disorder is less, the behavior of the subject is simpler rather than complex. The entropy of the subject is close to the entropy created by the movement of the mass, indicating that the tracking performance of subject is good, and IL is improved depending on it.

4.5 Kurtosis and Skewness

A statistical measure called kurtosis indicates whether a distribution is longer or shorter than a normal distribution. The Kurtosis value is 0 if a distribution resembles the normal distribution, whereas, when kurtosis is more than 0, the distribution has a higher peak than a normal distribution, and when kurtosis is less than 0, the distribution is flatter.

As for skewness, it can be used for determining whether or not a distribution is symmetric. If a distribution's right side and left side are similar, then the distribution is said to be symmetric and if it is symmetric, distribution's skewness value is zero.

The following equations are for calculation for the kurtosis and skewness [72]. Overlaps are calculated by using these metrics. Kurtosis versus skewness graphs are given in Chapter 5.

$$\text{Kurtosis} = \frac{\sum (x-\bar{x})^4}{(n-1)\cdot S^4} \tag{15}$$

$$\text{Skewness} = \frac{\sum (x-\bar{x})^3}{(n-1)\cdot S^3} \tag{16}$$

where S corresponds to standard deviation and $\bar{x}$ is the mean of the data. If kurtosis value of the subject is to be found x and $\bar{x}$ represent the position data of the subject and mean of it, respectively. As for n, it is the sample number throughout the simulation.

4.6 Similarity Level (SL)

The degree of similarity between two velocity time series is described by their mean skewness and kurtosis of normalized velocity segments as calculated below [73]:

$$SL = \sqrt{(\bar{s}_1-\bar{s}_2)^2+(\bar{k}_1-\bar{k}_2)^2} \tag{17}$$

where

$$\bar{s}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} s_{i,j} \tag{18}$$

$$\bar{k}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} k_{i,j} \tag{19}$$

Equation (18) and (19) are used for finding the similarity level between subjects and masses which is formulated in equation (17). $\bar{s}_i$ and $\bar{k}_i$ refers to skewness and kurtosis mean of normalized velocity segments, while n_i corresponds to number of normalized velocity segments in ith time. $s_{i,j}$ and $k_{i,j}$ represents to skewness and kurtosis value of jth normalized velocity segments [73]. The amount of synchronization between the subject and mass, good tracking performance and improvement in IL can be achieved by lower values of SL.

4.7 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical tool which provides opportunity to determine variance-based differences in means between two or more categorical groups, if there is a statistically significant difference between them. In addition to analyzing the data obtained from the subjects using metrics, ANOVA was used in this thesis to reveal it statistically. First, first-way ANOVA was performed between segments in the trajectory to demonstrate the presence of IL for 3 experiments. Since implicit learning does not vary from person to person and has invariability, first-way ANOVA also was performed among the subjects respectively. ANOVA matrices were created using RMSE, EMD, CV and entropy to prove the result of metric analysis as well.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, results and discussion of experiments are covered. Afore mentioned, 3 experiments are conducted to test the effect of the haptic interaction on transfer and retention of the IL. In addition, all experiments consist of 3 motivations which are observation of existence, transfer and retention of IL. Therefore, each motivation in every experiment was tested, and results and discussions are given in the followings.

5.1 Results and discussions for experiment 1

In experiment 1, subjects are tested as non-haptic group with 2 trials of training which was not used in data analysis, 10 trials for learning phase, 2 trials for testing phase for transfer, 1 trial for testing phase for durability after one day and 1 trial for testing phase of durability after one week.

5.1.1 Existence of IL in the experiment 1

Learning phase of 10 trials shows us the learning of repeated trajectory implicitly. Therefore, subjects are expected to improve their tracking performance in repeated segments which was located in the middle of the trajectory in each trial. Since IL has some characteristics like IQ and age independence and invariability, if IL exists during the experiment, it is easy to observe them from datum collected from the subjects. Considering that subjects have different age and IQ level, it is expected that results are not affected from them and are not varying between different subjects. As a result, if there is a significant difference between tracking performance in random and repeated segments and characteristics of IL can be observed in repeated segments of data, we can easily say that IL is occurred.

Metric values of each subjects and trials were calculated from the position and velocity data taken from the joystick and masses positions. Average EMD, RMSE, CV, SL and entropy of 10 trial and standard deviations of these trials of each subject for first, middle and last segment are calculated. Their bar graphs are given in appendix A.

EMD of most of the subjects in middle segment which was repeated segment are smaller than others which were random. Smaller EMD indicates that performance in the middle segment is better than other segments. Subjects learned the repeated trajectory and performed well gradually. In addition to the graphs, ANOVA was performed according to EMD matrices of the subject between segments and middle segment performance comes also slightly different from the others statistically.

In Fig. 5.1, lines represent each segment, and the first random segment has been named as group 1, middle repeated segment has been represented as group 2 and last random segment has been called as group 3. Since the p value of EMD based ANOVA is 0.7513 ($p>0.001$), we can say that the groups are close to heterogeneous, but there are also small differences.

As for RMSE of the subjects, this metric shows similar results as EMD. RMSE values are calculated by difference of positions of masses and subject. Obviously, position temporal correspondence of middle segment is lower than others. According to ANOVA analysis performed with RMSE matrices of subjects, repeated segment has means significantly different from other groups which are random. P value of the analysis is equal to $4.7898e^{-07}$ ($p<0.001$) which means groups are not homogeneous.

Furthermore, good tracking performance and synchronization are indicated also by a high circular variance score. Pertaining to experiment results, mean CV values of all subjects are similar to each other while standard deviations differ. By the same token, ANOVA was performed via circular variance. Obviously, two groups which are random groups are necessarily different than repeated segment with the p value of 0.0016 which is approximately heterogenic.

When it comes to similarity level between subjects and mass, it is expected to see greater SL in repeated segment due to existence of IL. The results also confirm the expectation. Bar charts of means of SL and standard deviations in 3 segments are also given in appendices. Regarding the results of SL, we can say that tracking performance of the subjects in middle segment is clearly different from the others thanks to IL. Greater SL shows that there is an improvement in tracking performance when we compare repeated segment to random segments.

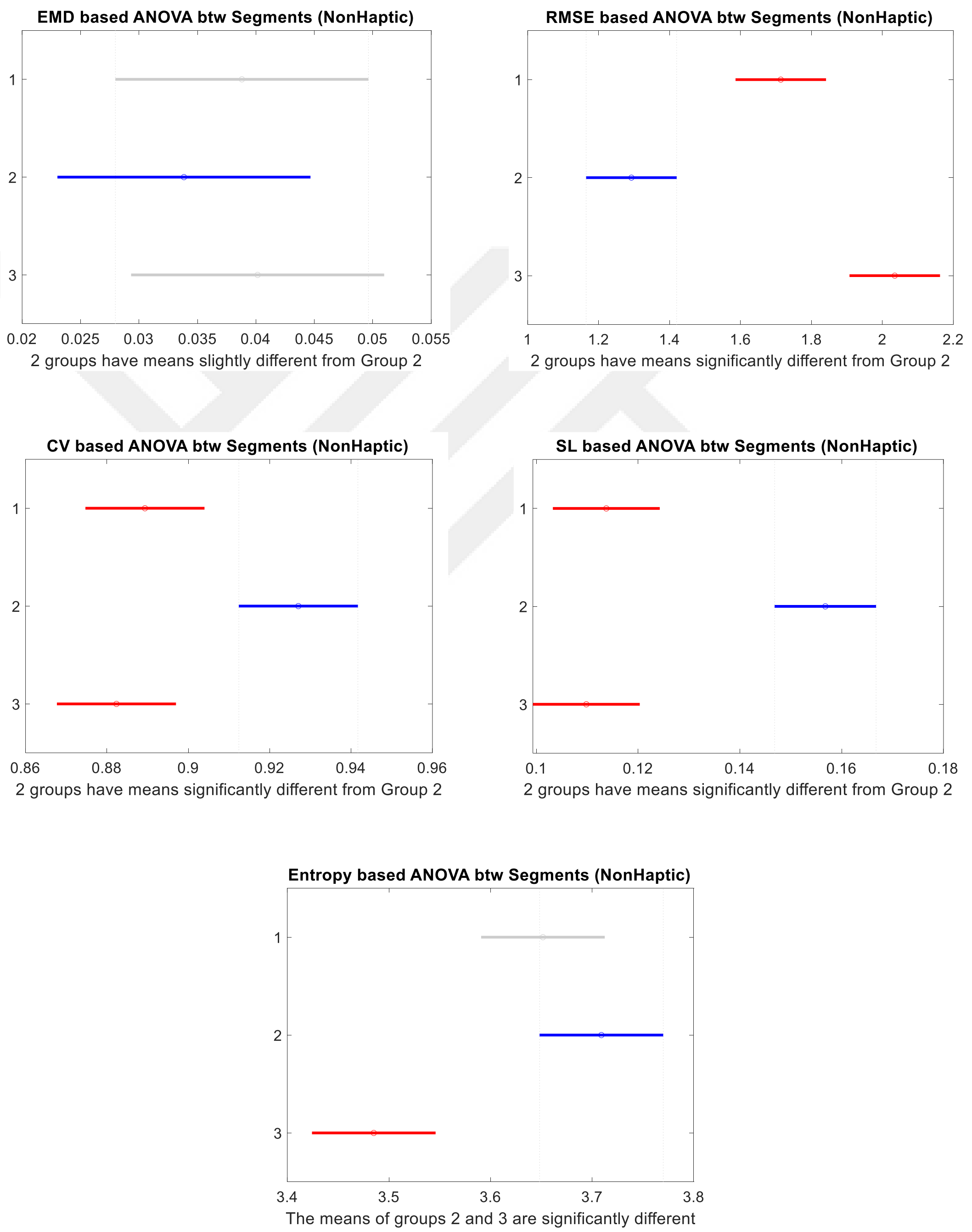


Fig. 5.1. ANOVA analysis between segments for EMD, RMSE, CV, SL and entropy in the experiment 1

Besides the metric analysis, ANOVA also proves the difference and existence of IL during repeated segment. Similarity level of middle segment has the greatest difference when it is compared with the other metrics. Its p value is also the smallest one which was 5.22 e^{-10} indicating that really heterogeny distribution.

In the case of entropy, low entropy means that there is less confusion, and that the subject's behavior is simpler rather than more complex. On the other hand, entropy results of subjects are similar because of the existence of random segments. Consequently, entropy metric analyses were performed but were weak in proving the existence of implicit learning in non-haptic condition. Coupled with metric analysis, ANOVA analysis was done. Furthermore, ANOVA analysis shows the difference between the last segments to others. P value of analysis 0.003 ($p>0.001$) shows that groups are slightly homogeny.

There is another situation where we can talk about the existence of IL, unlike metrics and ANOVA tests run according to metrics. As mentioned in the literature review, IL has some characteristic features. A few of them were different in age and IQ level and did not vary much from person to person. Since our experimental groups consisted of 10 subjects of different ages and IQ levels, we would actually expect to see some of these traits if IL had taken place.

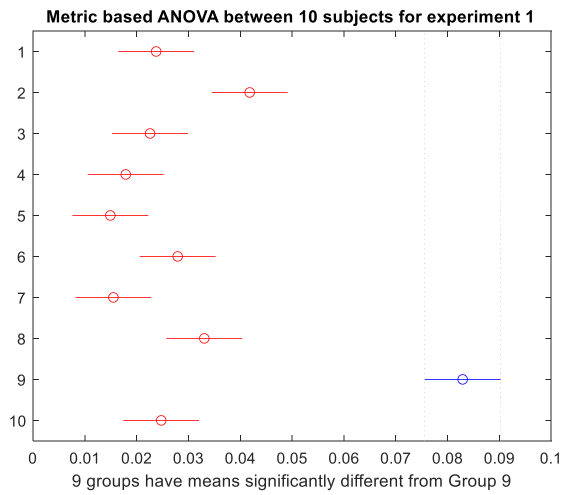


Fig. 5.2. ANOVA analysis between 10 subjects in the experiment 1

Table 5.1 ANOVA result between 10 subjects in the experiment 1

Source	SS	df	MS	F	Prob>F
Columns	0.3656	9	0.00406	39.9	$1.11832e^{-27}$
Error	0.00916	90	0.0001		
Total	0.04572	99			

Therefore, an ANOVA analysis was performed to make an inter-subject comparison over metrics but not between segments. It was seen that 9 out of 10 subjects were similar and only one person showed a different characteristic (See Fig. 5.2).

In ANOVA table given as Table 5.1, SS represents each sources' sum of squares value while df is each sources' degree of freedom. MS is mean squares and it is equal to ratio of SS/df and F value is mean squares' ratio. By using these values, probability value is calculated. A very low p value ($p= 1.11e^{-27} <0.001$) showed us that the data set was homogeneous and did not show variability, not affected by age and IQ level.

5.1.2 Transfer of IL in the experiment 1

In this condition, non-haptic group subjects participated in the testing phase with 2 trials. One of them has the same trajectory with the learning phase like final test (trial 11 of every subject) and other one has changed trajectory with moving repeated segment from middle to last segment (trial 12 of every subject).

Under this subheading, comparison of two testing phase trials and discussion on them are given. The subject and masses position map for trial 11 and 12 of all subjects are illustrated as given Fig. 5.3 and Fig. 5.4 properly.

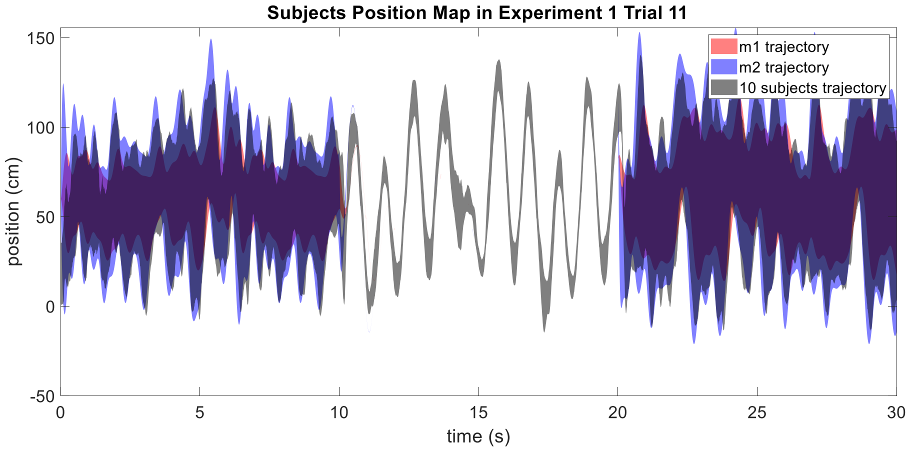


Fig. 5.3. Subject & masses position map of all subjects for trial 11 (repeated segment in the middle segment) in the experiment 1

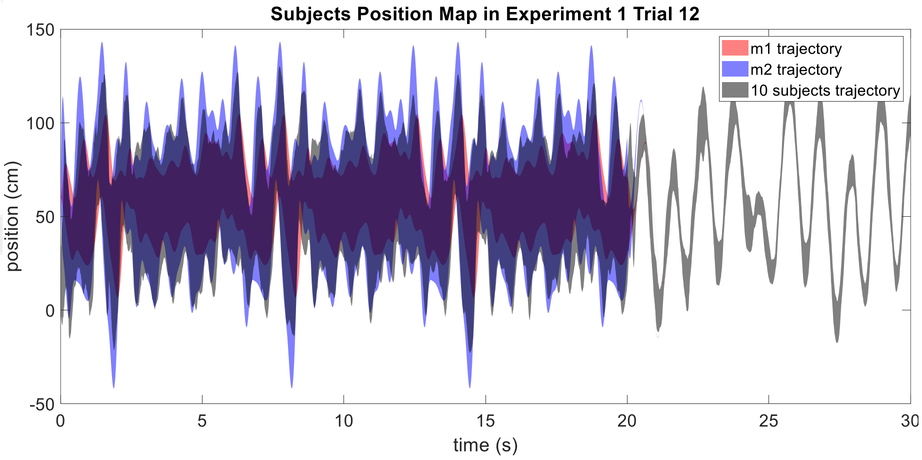


Fig. 5.4. Subject & masses position map of all subjects for trial 12 (repeated segment in the last segment) in the experiment 1

To see the difference between trial 11 and trial 12, kurtosis vs skewness maps are created as given below. (See Fig. 5.5.) Ellipses represent the masses' motion for each trial while dots represent subjects' motion. If dots stack towards the middle of the ellipses, it means better performance. Since kurtosis vs skewness maps result are similar like position maps, transfer performance was not as expected in experiment 1.

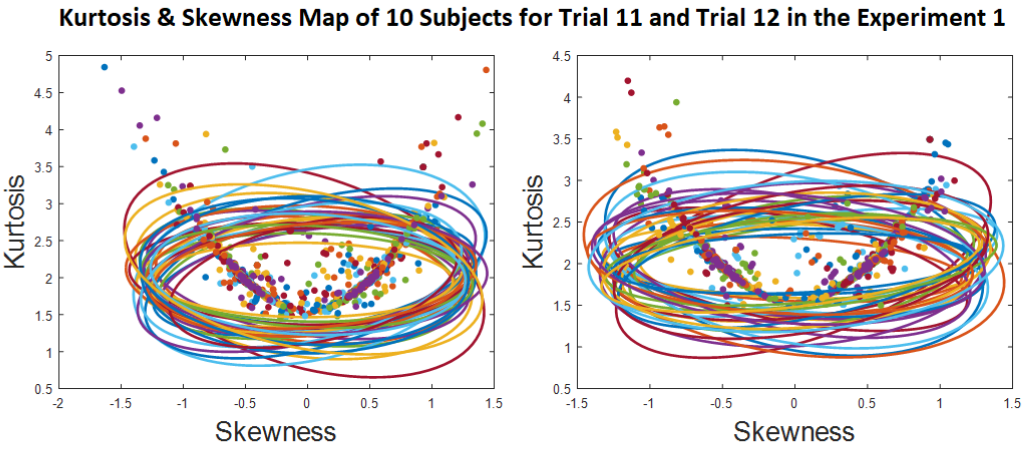


Fig. 5.5. Kurtosis vs skewness map for trial 11 and 12 in the experiment 1

The difference between trial 11 and trial 12 was not seen clearly from the above graphs. Therefore, EMD, RMSE, SL, CV and SE metrics are calculated for the repeated segments which were located in the middle for trial 11 and in the last segment for trial 12. The comparison of these metrics demonstrates that tracking performance of subjects in repeated segment decreases when it is moved to last segment. Nevertheless, it is obvious that the transfer of IL has not taken place, as there is deterioration in performance results of metrics.

5.1.3 Retention of IL in the experiment 1

To test the retention of IL, subjects were retested one day and one week after the first exposure of the experiment. These tests are conducted with the trajectory of learning phase since subjects are more familiar with it due to more training. If tracking performance of subject does not decrease after one day or one week, we can say that there is durability of IL. Results and discussion of retesting one day and one week are given in the following.

5.1.3.1 Results and discussion of retesting one day later

It is expected that tracking performance of subjects neither increase nor decrease by retesting one day after. Duration between learning phase and retesting should be kept long to see the difference. On the other hand, the reason why this test repeated a day later is to see if anything has changed. Trial 11 from the testing phase which has same trajectory with the learning phase was used for this comparison with trial 13 which is result for retesting after 1 day. While there are some changes in random segments, repeated segments for trial 11 and 13 are similar to each other.

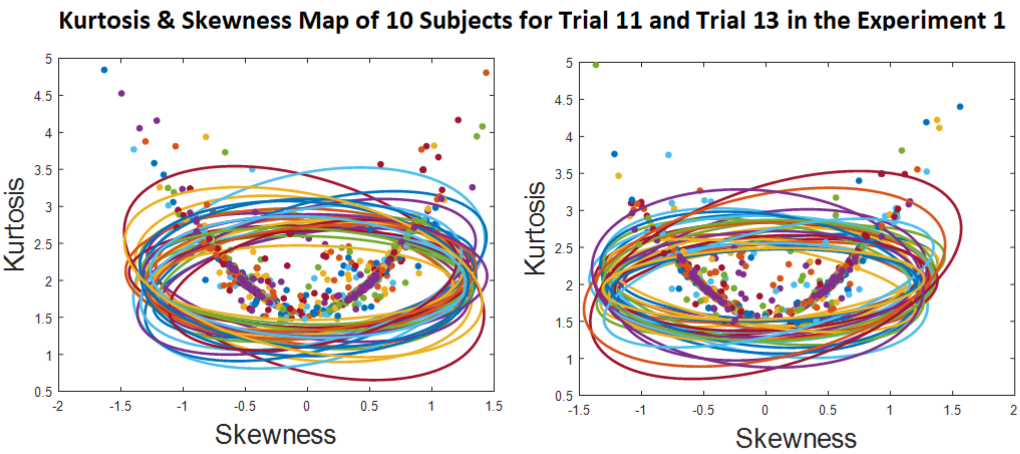


Fig. 5.6. Kurtosis vs skewness map for trial 11 and 13 in the experiment 1

Kurtosis and skewness maps for trial 11 and trial 13 of 10 subjects are given in Fig. 5.6. While dots are inside of the ellipses when it is compared to day before experiment, its skewness distribution changes and there is not symmetric distribution. As a result of the metric analysis given in Table A.7 (in appendix A), it was observed that there was not much difference, and even improvements in the performance of some of the subjects tested one day later.

5.1.3.2 Results and discussion of retesting one week later

Non-haptic group subjects are tested after one week from the learning phase to see the durability of IL. Experimental procedures were the same as before. Subjects' performance of tracking does not change as much when they participate in the experiment again after 1 week. The middle of the trajectory which is repeating segment was same as learning phase trajectory. Therefore, subjects are expected to learn the repeating segment movement implicitly and its durability is more than learning some rules explicitly. This conclusion can be drawn from these experiments. In below, kurtosis vs skewness map for 10 subjects is given. When looking at the permanence of the experiment, a decrease in performance could be expected as a week passed, but as can be seen in Fig. 5.7, we can even say that the irregularity in performance is reduced and there are improvements for whole segments from time to time, as the points are piled up inside the ellipses.

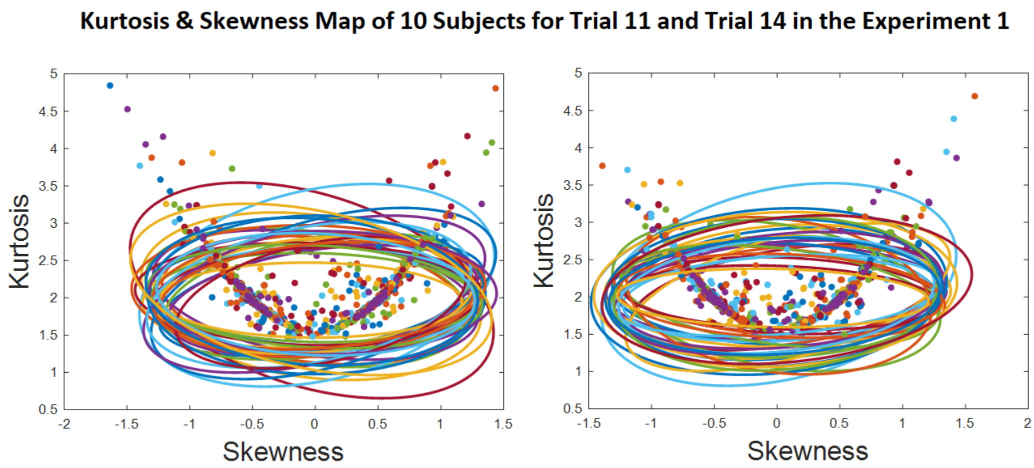


Fig. 5.7. Kurtosis vs skewness map for trial 11 and 14 in the experiment 1

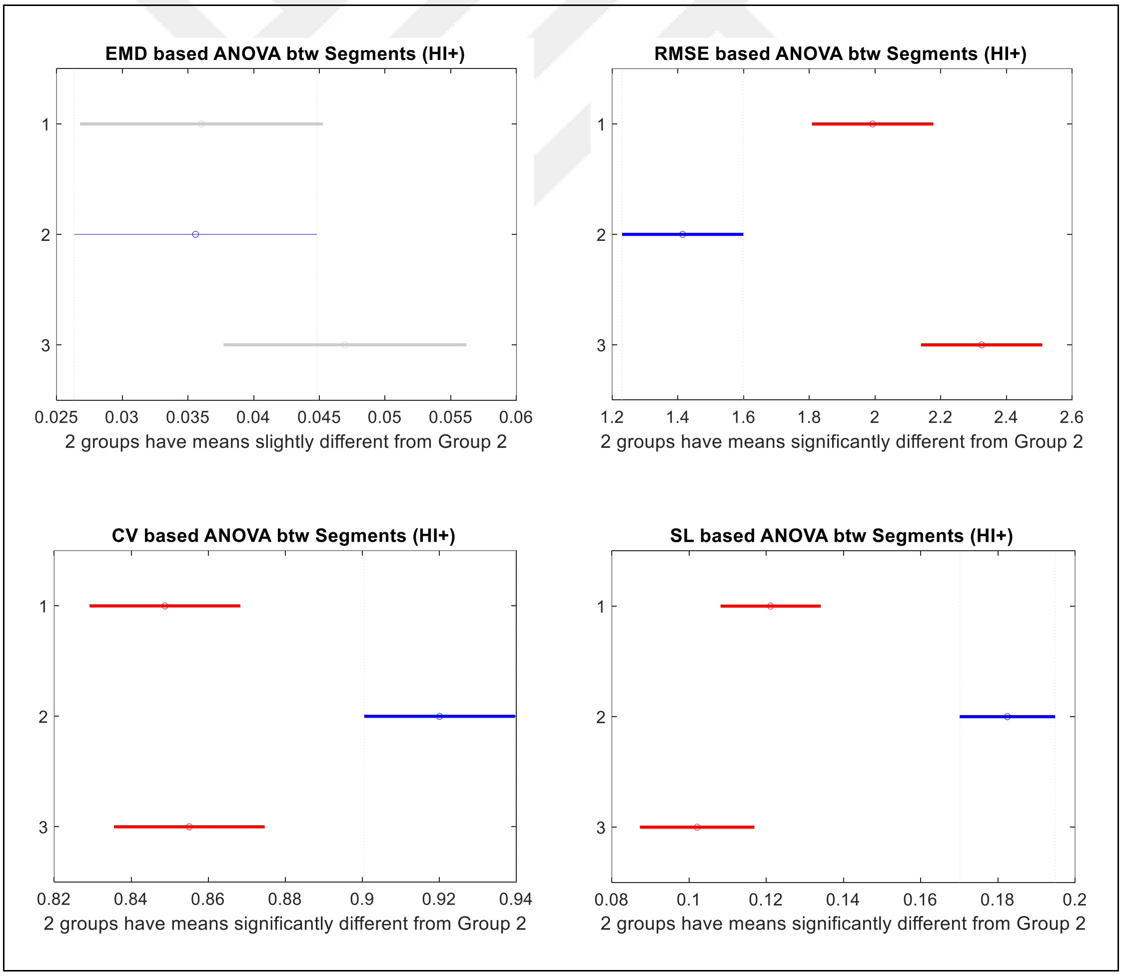
As for metrics results of the participants retested after one week, a little less than half of the subjects show improvement in experiments. When trial 11 is compared to trial 14, decrease SL value of 7 subjects is observed. In addition to SL, 6 out of 10 subjects' entropy, CV and EMD metrics show decrease in performance while 5 out of 10 subjects' RMSE value are decreasing. Results tell us that no major reductions in performance were seen, but there is a decline in implicit learning measures compared to a week ago. If the implicit learning were not permanent, there would be great declines in performance, and many subjects could have performed close to the practice phase performances as if they had not learned at all.

5.2 Results and discussions for experiment 2

Subjects are tested as assistive haptic group in experiment 2. Haptic guidance is applied to the joystick by using virtual spring modelling. In other words, the position response of the haptic force to the steering wheel joystick was fed as analog input, modeled as if subjects were connected to mass 1 by a virtual spring. When mass 1 moves to the right, this interaction guides the subject tactilely by directing the joystick in the right direction since position of mass 1 calculated beforehand.

5.2.1 Existence of IL in the experiment 2

The position and velocity data also obtained from the joystick and mass positions were used to generate the metrics for each person for every trial in experiment 2. The charts given in appendix B provide the average EMD, RMSE, CV, SL and entropy of 10 trials and the standard deviation for each participant for the first, middle, and last segments. Furthermore, ANOVA analysis between segments performed with EMD matrices, the mean of the middle segment is different from the last segment while there are minor differences between middle and first segments. P value of the ANOVA analysis which is equal to p=0.2425<0.001 indicates that approximately homogeneous result was obtained from the subjects of haptic assistive group.



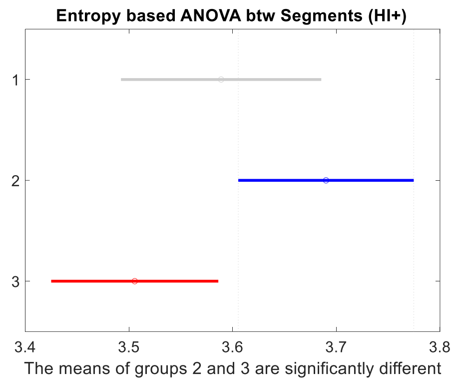


Fig. 5.8. ANOVA analysis between segments for EMD, RMSE, CV, SL and entropy in the experiment 2

Lastly, entropy of each subject in every segment are calculated for experiment 2. Since entropy values and ANOVA result based on entropy do not clearly give information about the existence of IL in experiment 1, they are calculated again in experiment 2 for comparison. ANOVA result for entropy in experiment 2 is similar with the experiment 1. While the middle and last segment differ, the middle segment is close to the first segment. Entropy values of subjects in the last segments are lower than others. However, we cannot deduce that the performance is better in the last segment from the low entropy values, because we do not know whether the incoming trajectory is easier compared to the other segments, since the trajectories are random in the first and last segment.

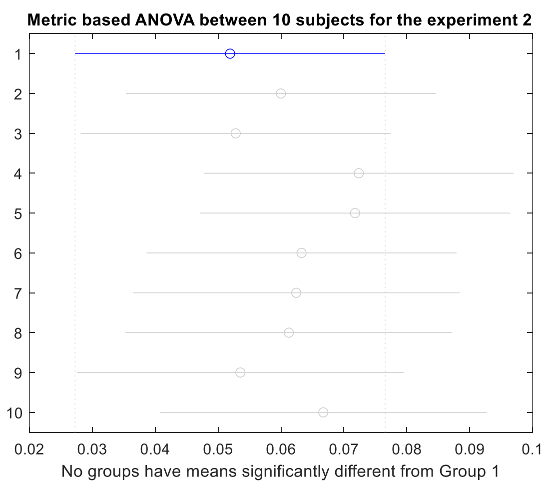


Fig. 5.9. ANOVA analysis between 10 subjects in the experiment 2

Table 5.2 ANOVA result between 10 subjects in the experiment 2

Source	SS	df	MS	F	Prob>F
Columns	0.00479	9	0.00053	0.46	0.8958
Error	0.09894	86	0.00115		
Total	0.10373	95			

To see the behavior of the IL from the subjects' performance, ANOVA is performed between subjects. The emergence of characteristic features of IL is observed accordingly. Unlike experiment 1, all subjects' means are close to each other in the experiment 2. ANOVA results and metric analysis indicate that the existence of IL is clearly observable in experiment 2 which has subjects affected by HI+. The most common features of IL which are age, IQ, subject independences are seen in the analysis results by homogeneity of the data for each subject.

5.2.2 Transfer of IL in the experiment 2

To test the transfer of IL in experiment 2, an assistive haptic interaction (HI+) group was created consisting of 10 different subjects from experiment 1. The same subjects in experiment 1 was not participated experiment 2 due to more clear data result and neglecting the effect of experiment 1 learning phase. So, testing phase of experiment 2 has the same conditions with experiment 1 except for assistive haptic interaction. Trial 11 shows the repeated segment located in middle segment while trial 12 shows repeated segment located in the last segment. Position map of subjects and masses for 10 subjects in trial 11 and 12 are given in appendix B.

When the repeated segment is moved from middle to last in experiment 2, it can be said that the tracking performance of the subjects did not change and even there was a small improvement. Kurtosis and skewness map for trial 11 and trial 12 was created according to their metric values as in Fig. 5.10. Since dots are closer to zero and inside of the ellipses in trial 12, it can be said that performance of subjects in trail 12 which means repeated segment moving to the last segment is better.

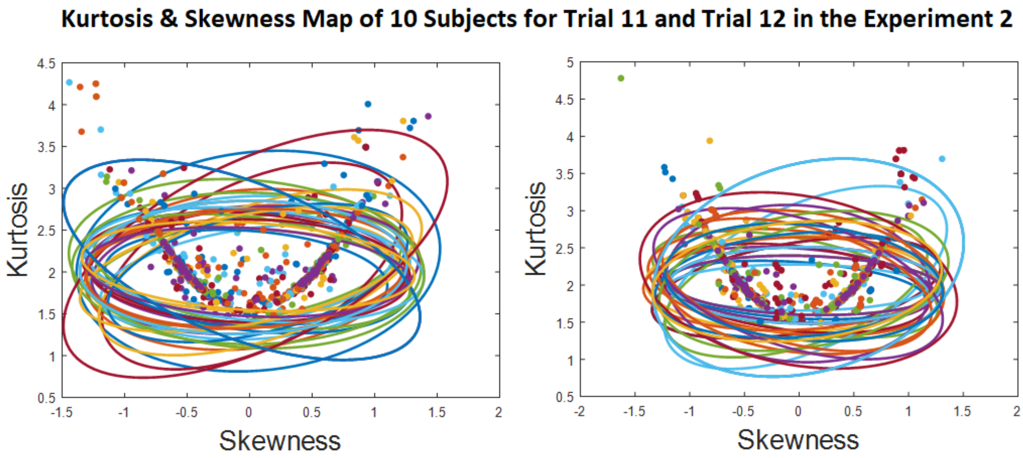


Fig. 5.10. Kurtosis vs skewness map for trial 11 and 12 in the experiment 2

With regard to metrics comparison given in Appendix B, the decrease in EMD, RMSE and SE values in the repeated segment moved to the last segment shows that there is an improvement on tracking performances and transfer of IL occurred in experiment 2. According to the metrics results of EMD and RMSE, 5 out of 10 subjects show improvement while the other half of the subjects' performances decrease. Additionally, entropy metric indicates that there is not occurrence of transfer of IL fully since 6 out of the 10 subjects have greater entropy values in trial 12. Conversely, higher SL and CV mean that subjects' synchronization and tracking performance develop. 7 out of 10 subjects have higher SL in trial 12 than in trial 11. As well as SL, 8 CV values of subjects are greater which mean that there is an improvement in tracking performance in repeated segment moved from middle to last. Hence, it is correct to say, based on metrics, that transfer took place in the second experiment compared to the first experiment. This throughput will be discussed later.

5.2.3 Retention of IL in the experiment 2

In this condition, assistive haptic interaction (HI+) subjects who participate the experiment 2 are retested one day and one week after from the learning phase. The same trajectory with learning phase and same haptic interaction are fed to joystick to clearly test the durability of IL. The following subheadings correspond the results and discussion of the retesting after one day and one week.

5.2.3.1 Results and discussion of retesting one day later

For the comparison, trial 11 from the testing phase, which follows the same trajectory as the learning phase, was employed. Trial 13 represents the outcome of retesting experiment 2, after one day. Since it is understandably seen from position maps given in Appendix B that variability of subject position in the repeated segment of trial 13 is little when it is compared with the repeated segment of trial 11. Furthermore, kurtosis and skewness map in addition to the EMD, RMSE, SL, CV and SE metric analysis for trial 11 and 13 are performed and given accordingly.

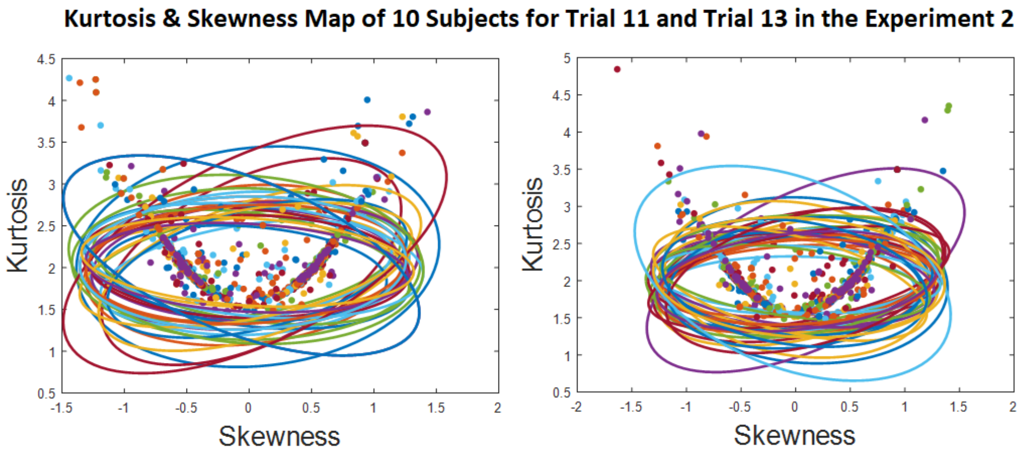


Fig. 5.11. Kurtosis vs skewness map for trial 11 and 13 in the experiment 2

EMD and RMSE values of the subjects in trial 13 are similar to in trial 11. While half of the subjects show improvement, other half of the subjects in trial 13 show deterioration in tracking performance. SL, CV and entropy also did not change much, as only one day had passed since the previous experiment.

5.2.3.2 Results and discussion of retesting one week later

Following the learning phase, assistive haptic interaction (HI+) group members are assessed to see retention of IL. The same experimental protocols as before were used.

Results from metrics and comparisons between trial 11 and trial 14 which is retesting after one week are provided successfully.

Since the distributions in the middle part of the trajectory are less, it can be commented that the performance in the repeating segment does not decrease. On the other hand, the kurtosis vs skewness map is given in the Fig. 5.12 below, which gives information that the follow-up performance of the subjects did not decrease.

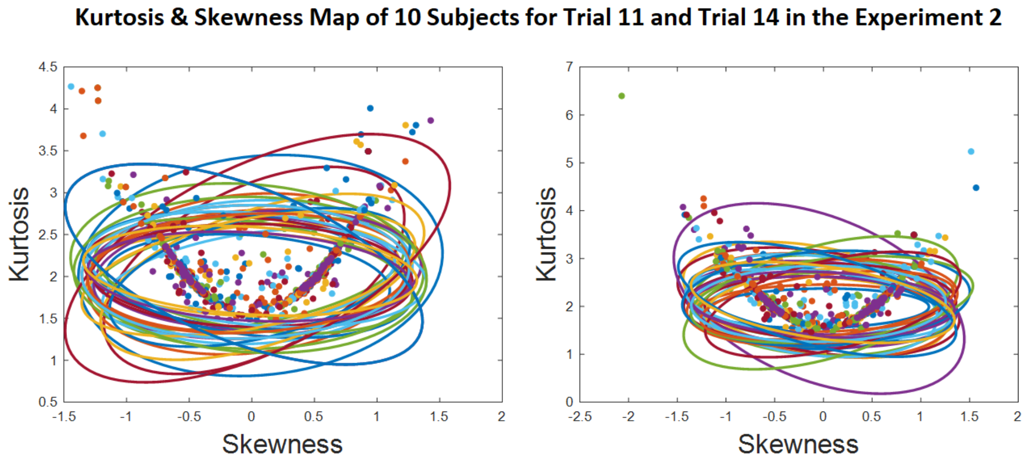


Fig. 5.12. Kurtosis vs skewness map for trial 11 and 14 in the experiment 2

It can be said that metrics results for testing one week after is better than non-haptic group subjects. While RMSE, CV and SE metrics results indicate that there is an improvement in tracking performance during trial 14, EMD of the subjects' decreases. 3 out of 10 subject performance decrease comparing the one week before performance which is right after the learning phase. Moreover, SL of 6 subjects is higher than one week before because of the permanence of IL.

5.3 Results and discussions for experiment 3

In experiment 3, participants are grouped as resistive haptic group which consist of 10 subjects like experiment 1 and 2. The joystick is exposed to haptic disturbance via virtual spring modeling. The steering wheel joystick's position reaction to the haptic force was provided as analog input, simulating how subjects would be connected to mass 1 by a spring in the physical world. Nonetheless, this interaction instructs the subject tactilely by moving the joystick in the opposite direction of experiment 2 and mass 1. Therefore, when mass 1 moves to the right, joystick command direction is fed as moving left side.

5.3.1 Existence of IL in the experiment 3

To show the existence of IL in experiment 3, the same metrics and ANOVA tests are performed according to defined metrics in chapter 4. The difference between subjects' mean EMD of all trials in the repeated segment and random segments is plainly observable from the bar figures given in appendix. The lower EMD in the middle segment of the trajectory which was repeated indicates that there is better synchronization of subjects. In accordance with EMD based ANOVA result, it shows the distinction between segments and group 2 which represents middle and repeated segment and random segments. The repeated segment varies from others in terms of having lower EMD values. P value ($p=0.02$) of the ANOVA analysis means that there is little homogeneity between segments.

Since the RMSE metric gives directly information about the tracking performance of the subjects, it can be said that position temporal correspondence of subjects is lower in the middle segment by looking metric values of each subject. ANOVA result based on RMSE also verifies the metric analysis.

In addition to EMD and RMSE analysis, CV is another metric which was used to evaluate the existence of IL. Almost half of the CV of resistive haptic interaction group subjects are similar for 3 segments while the other half of subjects show better performance based on CV. By looking at the ANOVA result based on CV, while there is significant distinction between first segment and the middle segment, the performance in the last segment is close to the performance of the first and middle segment. This brings us a little homogeneity ($p=0.0015>0.001$).

The metric where the difference between the segments is most clearly seen is SL. Because, the SL values in the repeating segment are very high compared to the others numerically and the difference is clearly visible. The ANOVA analysis is another proof of this difference. There is such a big distinction between the segments that the p value ($p=5.37e^{-10}<0.001$) is very low and brings heterogeny distribution.

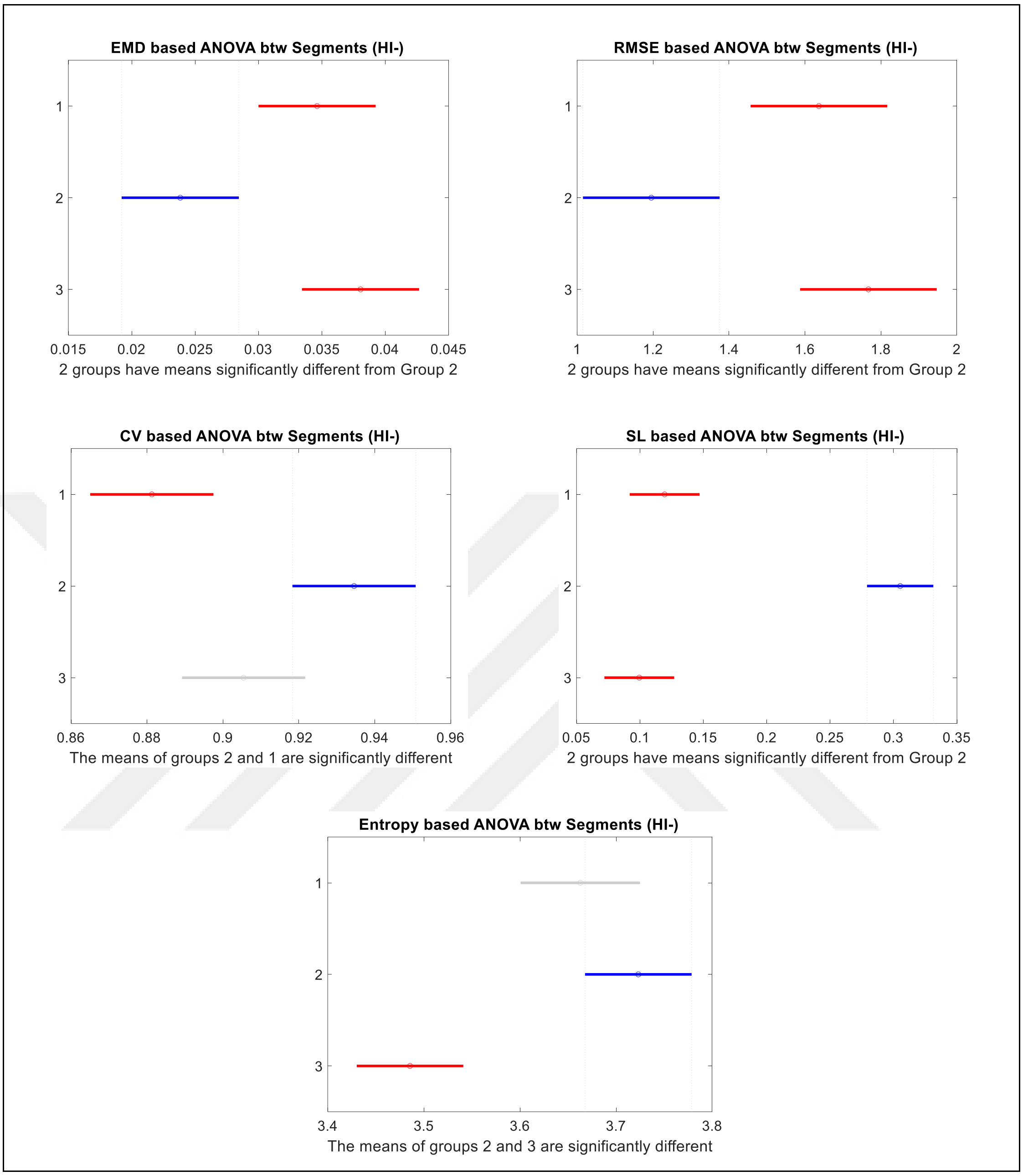


Fig. 5.13. ANOVA analysis between segments for EMD, RMSE, CV, SL and entropy in the experiment 3

Although the entropy analysis was carried out as in the other two experiments, it did not produce very different results in this experiment. There was no difference in the entropies of the subjects due to the change in segments. This may be because, as mentioned before, the first and last segment were random for each trial of subjects and this added disorder to the subject, causing the entropy to be similar. According to ANOVA analysis with entropy matrices, the middle segment is similar to the first segment even though the last and middle segments are different. The subjects in the last random segment have lower entropy values than the rest. In addition to analysis, the p value of entropy-based ANOVA which is equal to $4.72e^{-05} < 0.001$ represents the difference.

ANOVA is carried out amongst participants in order to observe the behavior of the IL from the performance of the individuals. In accordance with this, the emergence of IL's distinctive qualities is seen.

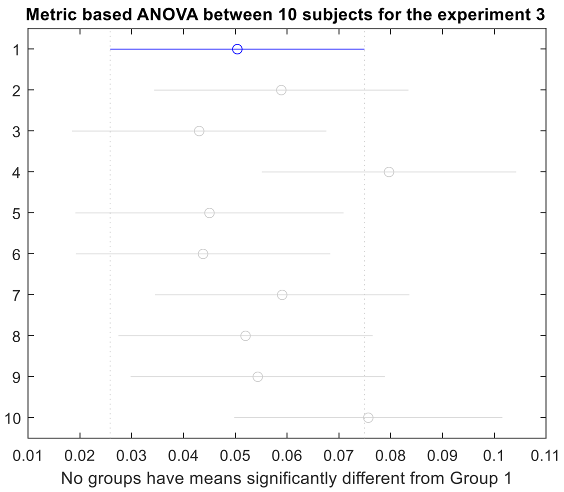


Fig. 5.14. ANOVA analysis between 10 subjects in the experiment 3

Table 5.3 ANOVA result between 10 subjects in the experiment 3

Source	SS	df	MS	F	Prob>F
Columns	0.01402	9	0.00156	1.36	0.2172
Error	0.10058	88	0.00114		
Total	0.1146	97			

As in Experiments 1 and 2, although the subject groups, ages, and IQ levels were different, the performance of the subjects was similar in Experiment 3. Since this is a characteristic feature of IL, it gives us the opportunity to talk about the existence of IL.

5.3.2 Transfer of IL in the experiment 3

A group of 10 distinct participants from experiment 1 and 2 were established to assess the transmission of IL in experiment 3, using resistive haptic interaction (HI-). The experimental settings for experiment 3 are identical to those of experiments 1 and 2. In trials 11, the repeated section is seen to be in the center of the segments while it is moved to last segment in trial 12. There was no such distinction between position maps of subject given in appendix C in trial 11 and 12. Therefore, kurtosis and skewness map and metric analysis are also performed to test the skill transfer of IL and results are shared as below Fig. 5.15.

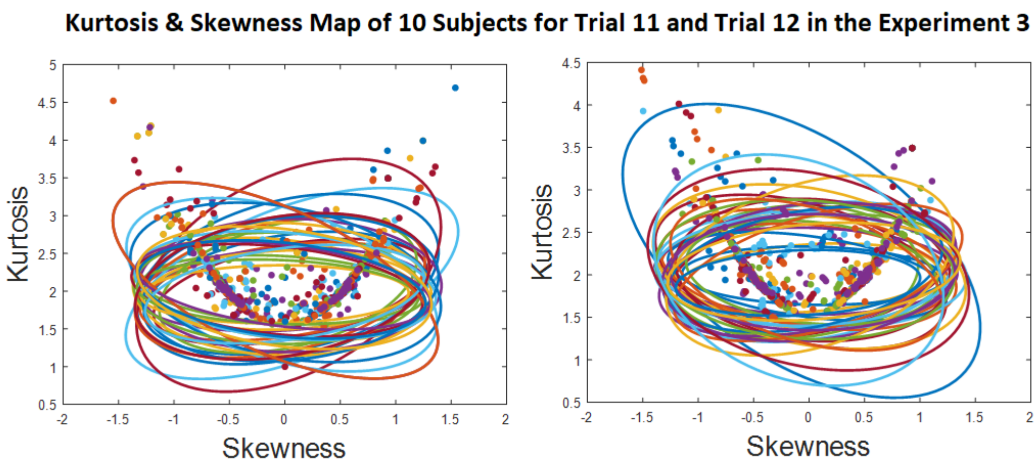


Fig. 5.15. Kurtosis vs skewness map for trial 11 and 12 in the experiment 3

According to Table C.6 in Appendix C, CV and entropy metrics show similar results that 7 out of 10 subjects improve their performance in trial 12 which has trajectory of repeated segment into the last segment. Unlike experiment 1 and 2, transfer of IL experiment failed by looking the EMD metric. However, RMSE values of trial 12 are lower than trial 11. 8 out of 10 subjects' performance of tracking develops in trial 12 by looking the RMSE values, since 6 out of 10 subject also shows similar behavior via SL values.

5.3.3 Retention of IL in the experiment 3

Subjects in experiment 3 who participate in resistive haptic interaction (HI-) are retested one day and one week following the learning phase in this condition. To clearly verify the longevity of IL, the same trajectory with the same learning phase and the same haptic force are given to the joystick. The results and discussion of the retesting after one day and one week are covered under the following subheadings.

5.3.3.1 Results and discussion of retesting one day later

The testing phase's trial 11, which has the same structure as the learning phase, was applied. The results of experiment 3's second round of testing are shown in trial 13.

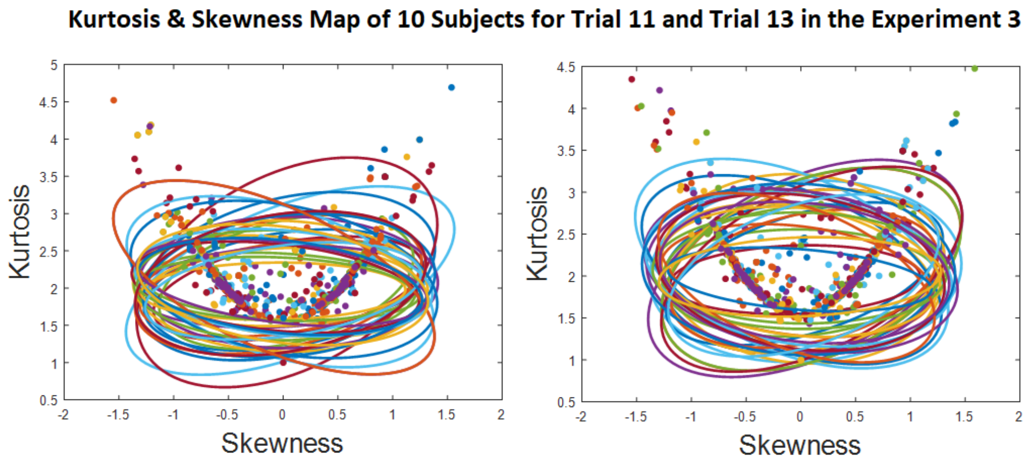


Fig. 5.19. Kurtosis vs skewness map for trial 11 and 13 in the experiment 3

Since there were not many changes in trial 11 and trial 13 from above figure (See Fig. 5.19) visually, metric analysis is performed based on EMD, RMSE, SL, CV and entropy for 10 subjects. While more than half of the subjects’ performance are similar with trial 11 and trial 13, it can be said that performing the experiment a day later doesn't change much. The subject neither forgets the experiment nor plays much better than the previous day.

5.3.3.2 Results and discussion of retesting one week later

Resistive haptic (HI-) group subjects participated in the experiment again after one week to observe the retention of IL. Comparisons between trial 11 and trial 14 are made as in the following. The comments in experiments 1 and 2 also apply to experiment 3. Kurtosis vs skewness map and metric results are shared as below.

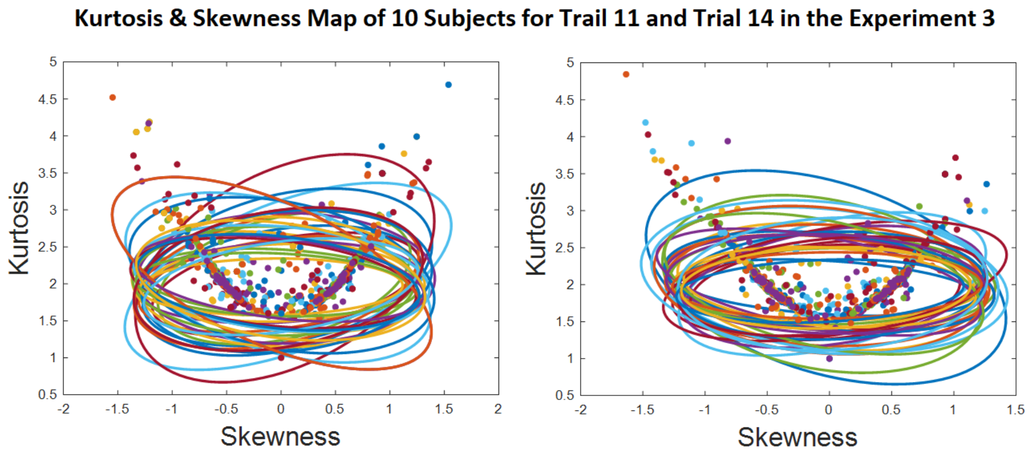


Fig. 5.20. Kurtosis vs skewness map for trial 11 and 14 in the experiment 3

Metric results for retesting subjects in experiment 3 which consists of participants exposed to the haptic disturbance during the experiment are interesting. Different from others, all subjects' similarity level with the following mass is higher than SL of the trial 11. In addition, entropy, CV and RMSE of the subjects are not decreased in trial 14 after retesting. On the contrary, subjects' performance decreases in EMD metric.

5.4 Discussion for Experiment 1, 2 and 3

The main purpose of dividing experiments into 3 groups is that the performance of individuals in a group who may or may not be exposed to assistive or resistive haptic interaction should not be affected by test exposures. Afterwards, 3 test phases and learning phases were tried for each experimental group. The metric and ANOVA results of all of them are shared. The comparison of these 3 experiments for different conditions will be examined under this heading.

Firstly, learning of the repeating segment in the middle was tested by participating in the experiment 10 times by the subjects of the 3 experimental groups. Whether learning takes place or not and the emergence of IL are discussed over metrics and ANOVA analysis. When the repetitive segment for IL is compared for each experiment, we can say that the degree of implicit learning is higher in the 3rd experiment. This can be the result of the subjects following more intently as a result of the disturbances. In studies in the literature, it was emphasized that disturbances are good for increasing task performance and motor variability. At the same time, the subjects try to lower their entropy by making better predictions. This positively affects the performance of participants when RHI is applied. 4 of the 5 main metrics used in this study clearly show that the best occurrence of IL is in experiment 3. The best performances were seen in experiment 2 only for the SL metric. This may be because the AHI helps the subjects, making it easier for the subjects to follow even when their concentration is impaired.

The trajectory of the experiment was modified during the test phase to look at the transfer of IL. Subjects performed their 12th trial with the middle repeating segment replaced at the end. As a result, the subjects' performance was expected to decrease a bit as a result of a trajectory they had learned implicitly was in the middle of nowhere. However, the results were not at all as expected. Although the repeating segment was moved to the end of the trajectory, repeating segment performance of some subjects' improvements were observed. On the other hand, these improvements were only seen in experiments 2 and 3. Conversely, transfer did not occur in experiment 1, and almost all subjects showed a decrease in follow-up performance. In fact, there were some statements in the literature that if you want to transfer IL, first turn the implicit to explicit. Even so, in the case of haptic interaction, the transfer of IL skill was well affected. The metric analysis results are almost equal for experiments 2 and 3 and the metrics used show that the transfer takes place in a positive way in experiment 2 and experiment 3. Therefore, it is not clear whether the assistive haptic or the resistive haptic is good for transfer. Nonetheless, it is obvious that the haptic interaction has a positive effect.

The experiment was performed one day later on the subjects of each group separately to check the persistence of the implicitly learned trajectory. There was not much change in performance. After 1 day, it was not expected that what was learned about the experiment would be forgotten. On the contrary, retesting 1 week later, retention of the IL does not expect too much from the subjects. While some subjects verify this statement, half of the subjects prove that there was durability of IL by existing improvement in 1 week after experiments. Looking at the results of the metric analysis, it can be said that the experiment with the most permanent learning is the 3rd experiment for retesting after 1 day and 2nd experiment for retesting after 1 week. If we consider that the best formation of IL is in the 3rd experiment, it is possible to say that the subjects of the 3rd experimental group are more permanent as they learn better. Also, a characteristic of IL is its robustness. While we easily forget something we learn explicitly, IM is more durable because it is more robust. It was observed that the haptic interaction helped the performance improvements by giving haptic clues to the subjects about transfer and retention and accelerating their motor learning in the experiments.

CHAPTER 6

CONCLUSIONS

6.1 Remarks

This study is motivated to understand social interaction by using developed experimental setup to examine the synchronization, prediction and implicit learning. Another main motivation is to reveal the relationship between HI and IL. Moreover, effects of AHI and RHI on occurrence, transfer and retention of IL are observed via 3 experimental setups.

Experiments were established as non-haptic, assistive haptic interaction and resistive haptic interaction. Experimental setups consist of animation of DMSDS for visualization and steering wheel joystick for data collection and providing the haptic interaction. In addition, designed trajectory which has first and last segments randomly generated and repeated segment in the middle was used. 30 subjects participated in the experiments, with 10 participants in each group.

In all 3 experiments, it was observed that learning took place implicitly, as the performances in the repeating segment gradually improved. Although the subjects' ages and IQ levels were different, there was no variation in the data between subjects. Since these features are the characteristics of IL, in addition to the ANOVA and metric analyzes that the learning takes place implicitly in all three experiments, it was possible to add the characteristic features to these analyzes. When all the experiments were compared within themselves, it was revealed with the metrics that the subjects who applied RHI were better at learning in the 3rd experiment. This showed that disturbances add well to motor learning and improve performance of IL.

As for transfer of the IL, while the transfer did not occur clearly in experiment 1, the transfer took place in the 2nd and 3rd experiments. Even some subjects in haptic interaction groups improved their performance.

Lastly, durability of IL is tested in all experiments by retesting subjects after 1 day and 1 week from the first exposure of the experiment which means learning phase day. While nothing much changed in the experiment the next day, some changes were noticeable in the experiment that was tried again 1 week later. Experiment 3 subjects' performances are better when compared to groups of other experiments. It was thought that this was due to the fact that the learning of the 3rd group was better due to haptic disturbance. Learning better can be more permanent and increases the durability of IL.

In conclusion, this thesis summarizes social interaction, synchronization, prediction, implicit learning and haptic interaction research in literature and defends its hypotheses by using metrics and statistical methods and finds answers to research questions with the experimental setup established to understand these concepts.

6.2 Future works

This study can be further developed in the following aspects:

- The number of subjects can be increased to conduct data analysis in a wider scope.
- New experiments can be designed to evaluate the effects of under actuation and control system on the implicit learning.
- Experiments can be conducted by changing haptic interaction models.
- Experiments can be done with various patient populations like amnesic, clinical depression or Korsakoff's syndrome etc.
- Explicit motor learning tasks can be defined and comparison between EML and IML can be made.

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APPENDICES

A. Experiment 1 (Nonhaptic) Results

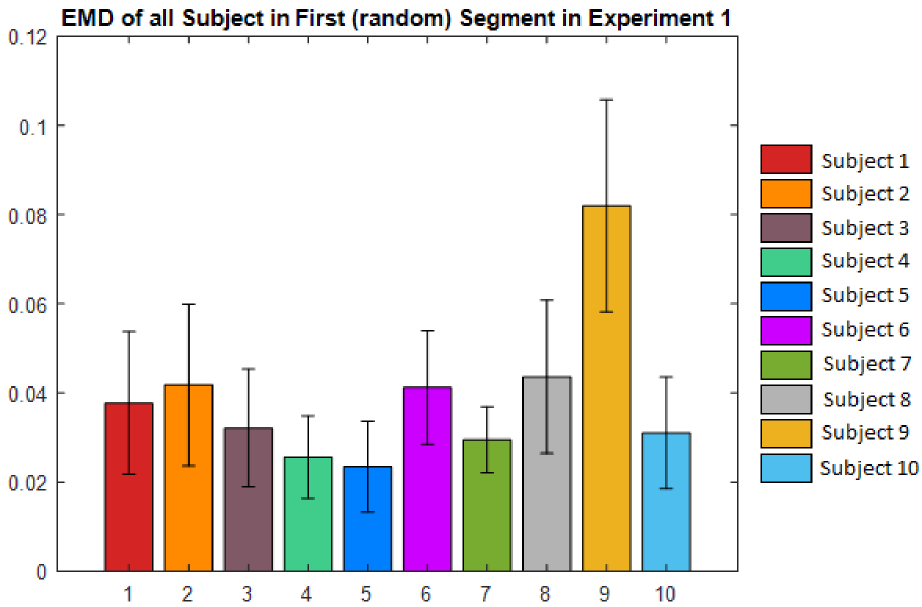

Fig. A.1. EMD of 10 subjects in first segment of the experiment 1

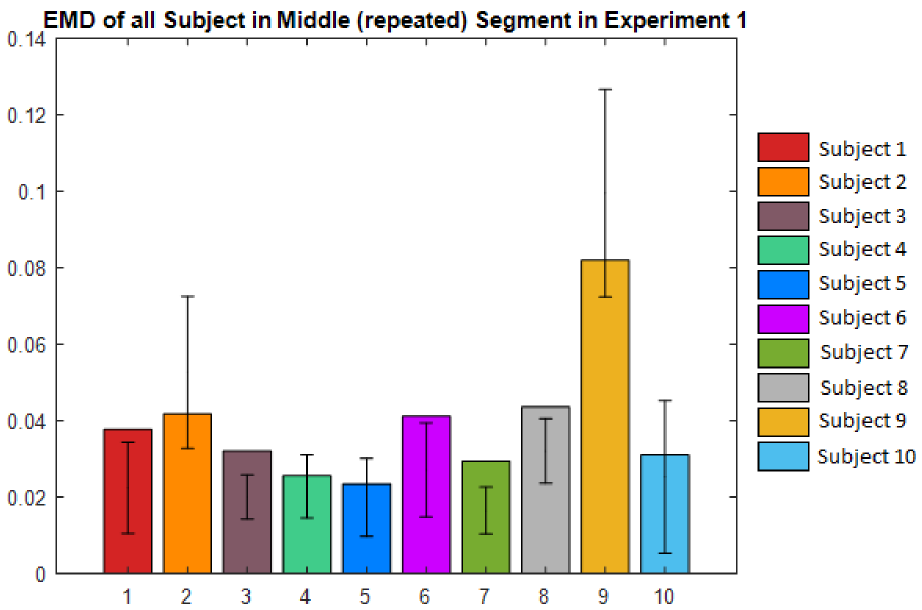

Fig. A.2. EMD of 10 subjects in middle segment of the experiment 1

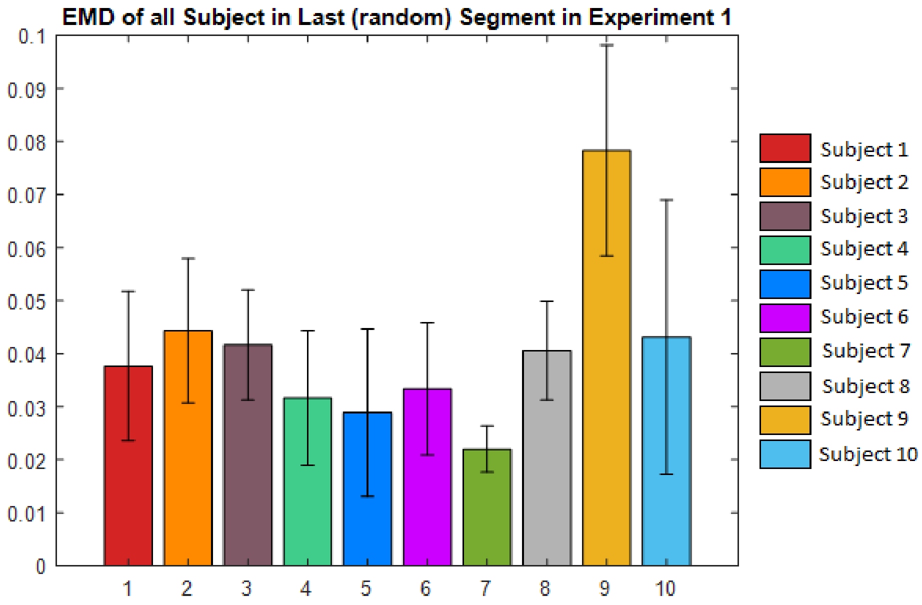

Fig. A.3. EMD of 10 subjects in last segment of the experiment 1

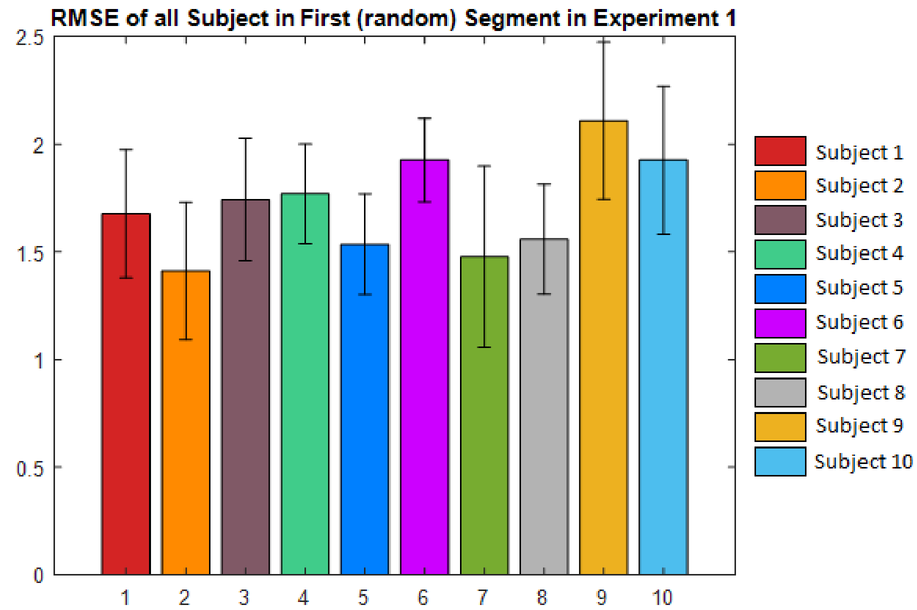

Fig. A.4. RMSE of 10 subjects in first segment of the experiment 1

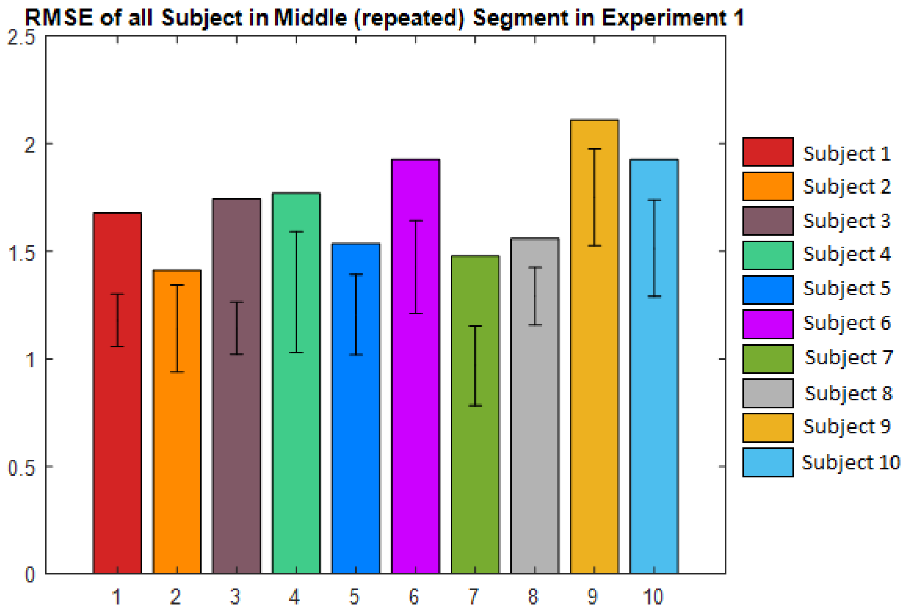

Fig. A.5. RMSE of 10 subjects in middle segment of the experiment 1

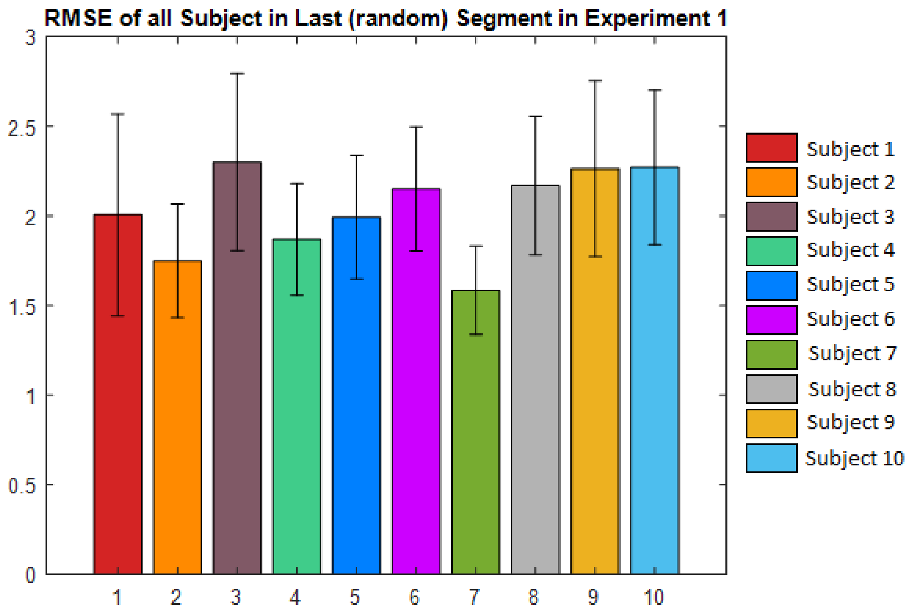

Fig. A.6. RMSE of 10 subjects in last segment of the experiment 1

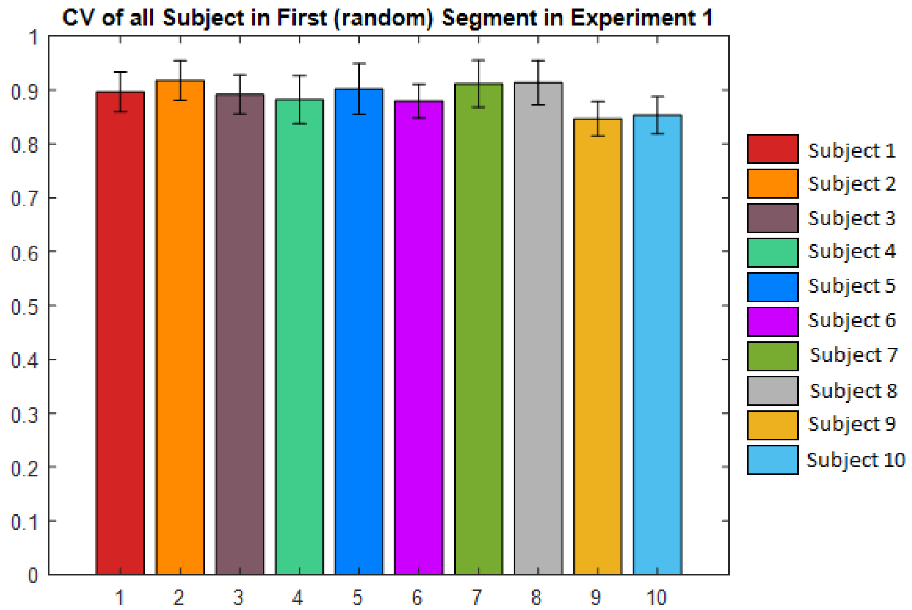

Fig. A.7. CV of 10 subjects in first segment of the experiment 1

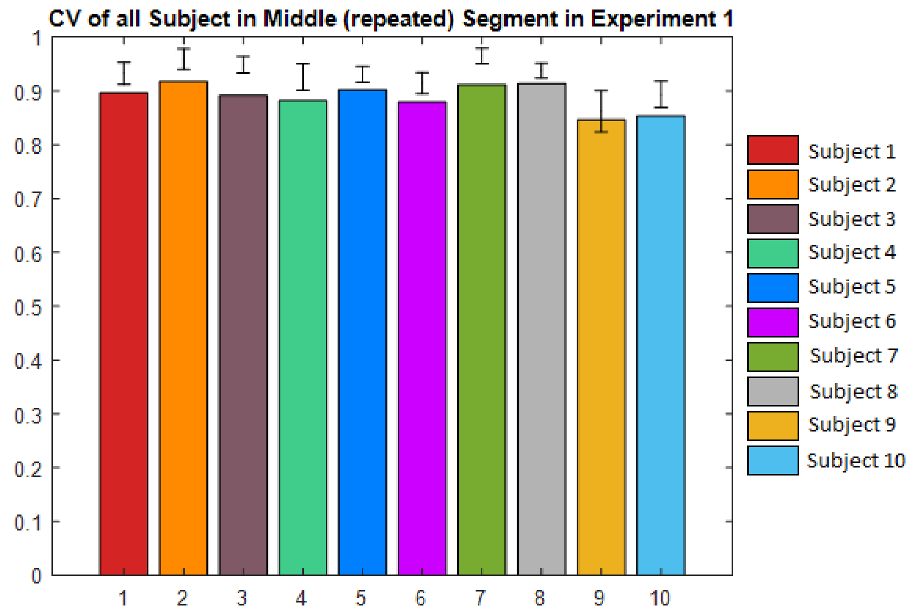

Fig. A.8. CV of 10 subjects in middle segment of the experiment 1

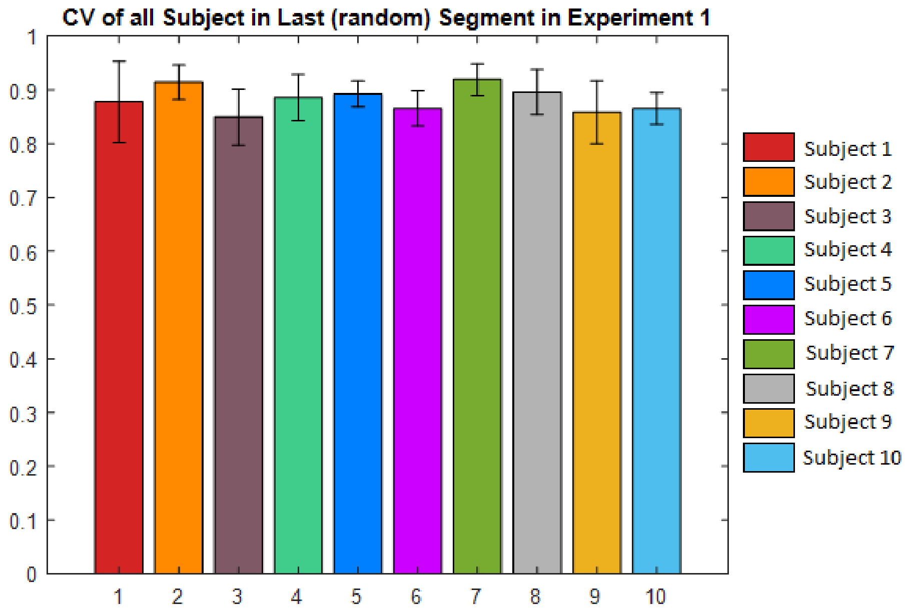

Fig. A.9. CV of 10 subjects in last segment of the experiment 1

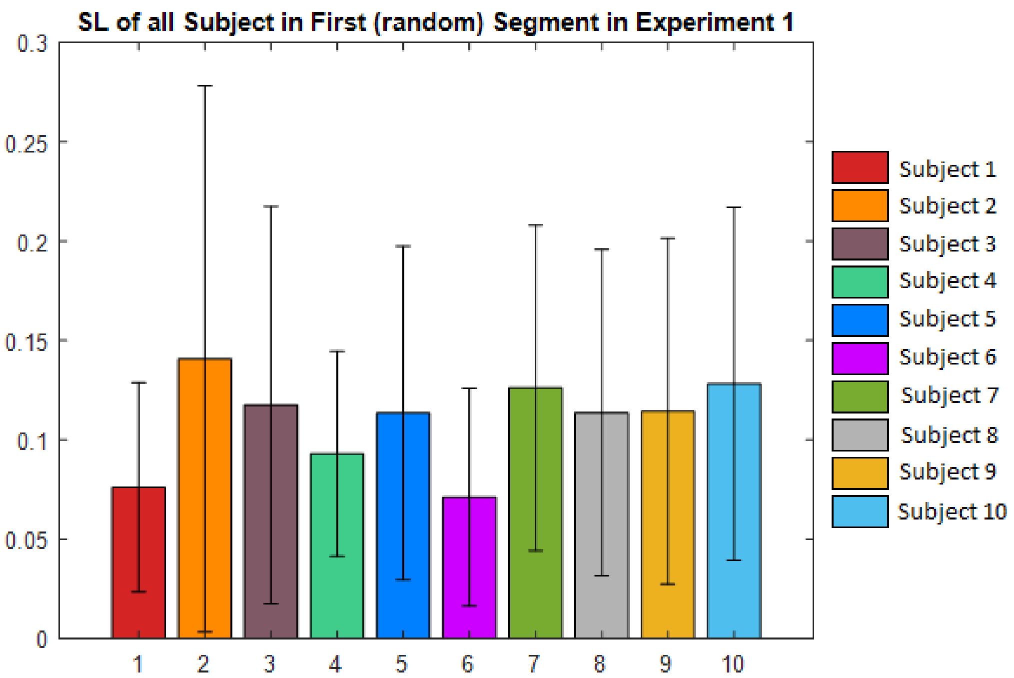

Fig. A.10. SL of 10 subjects in first segment of the experiment 1

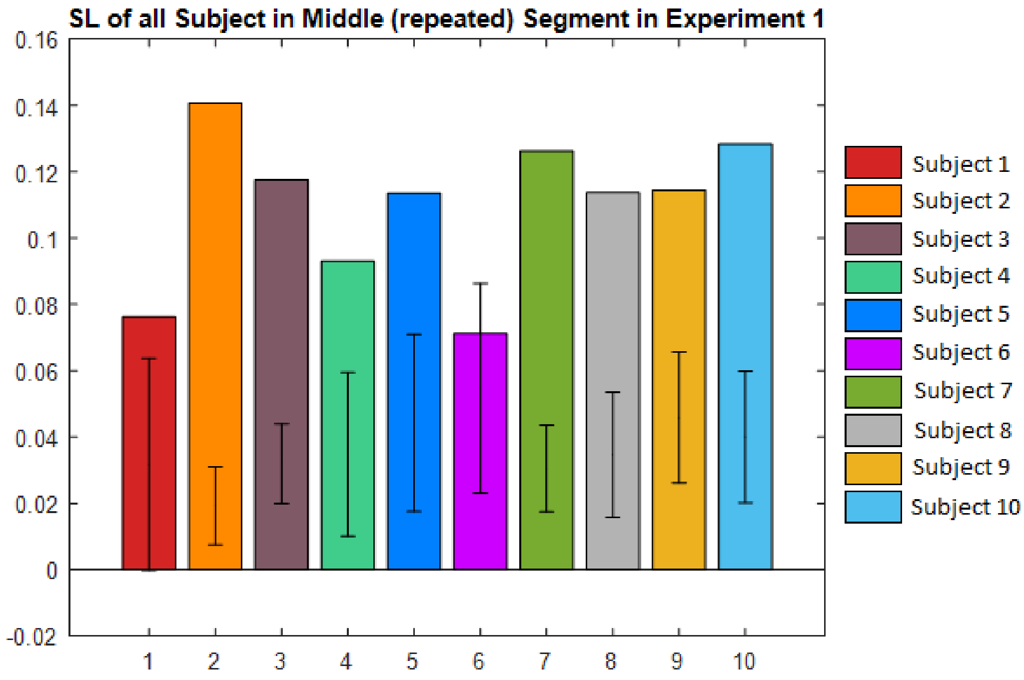

Fig. A.11. SL of 10 subjects in middle segment of the experiment 1

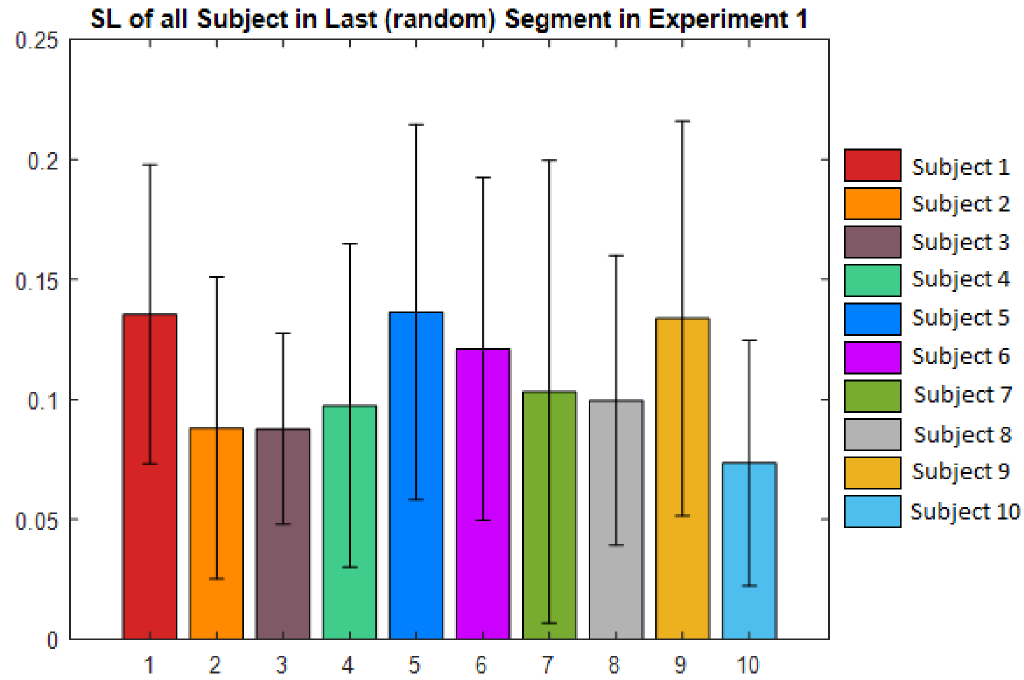

Fig. A.12. SL of 10 subjects in last segment of the the experiment 1

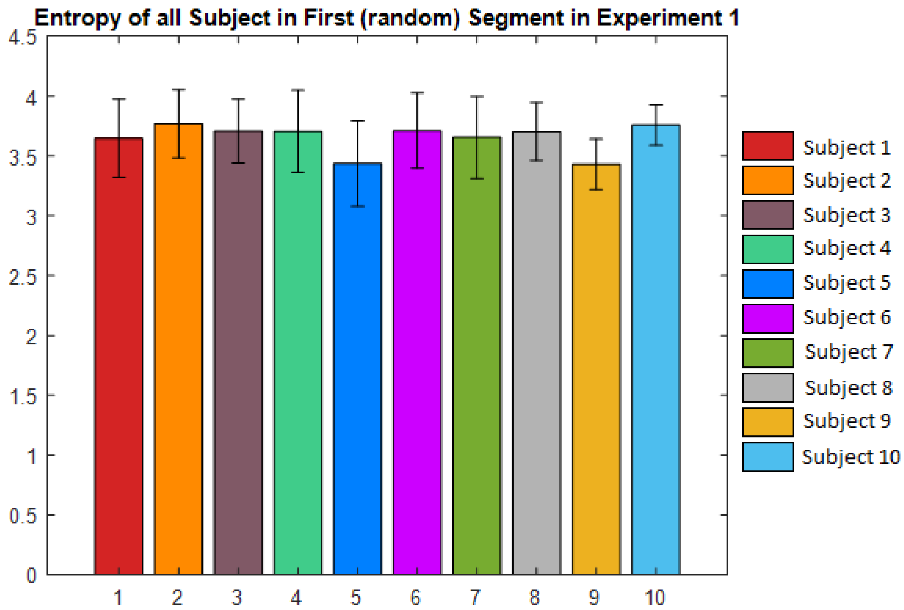

Fig. A.13. Entropy of 10 subjects in first segment of the experiment 1

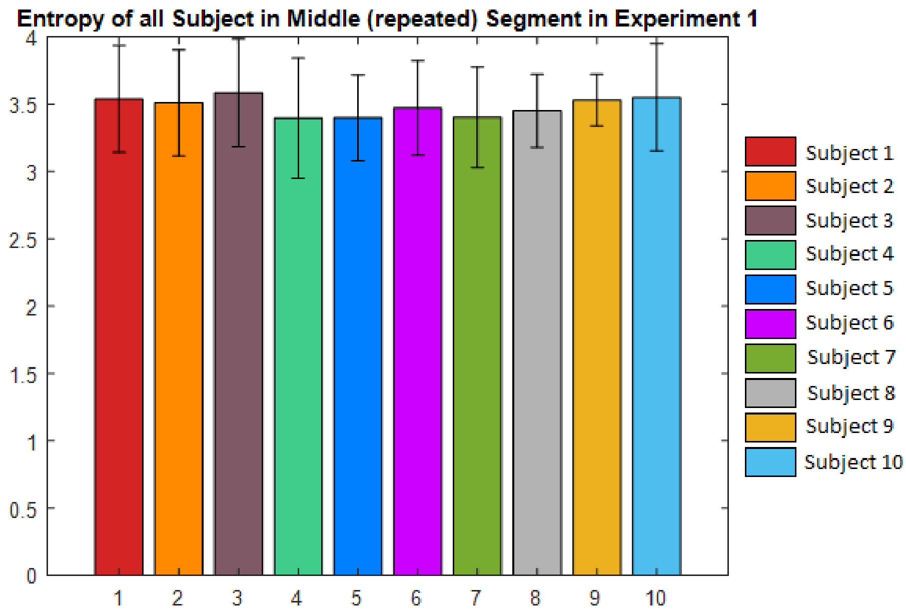

Fig. A.14. Entropy of 10 subjects in middle segment of the experiment 1

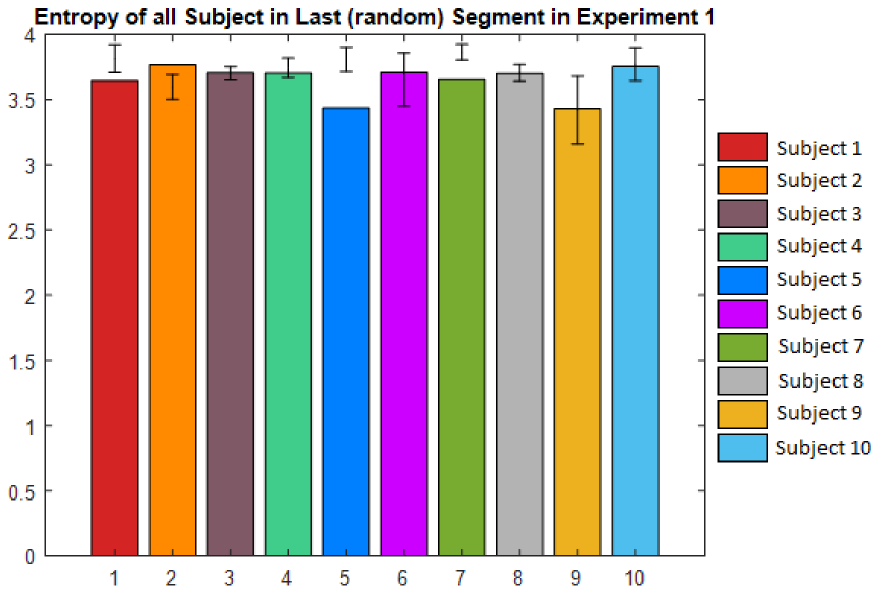

Fig. A.15. Entropy of 10 subjects in last segment of the experiment 1

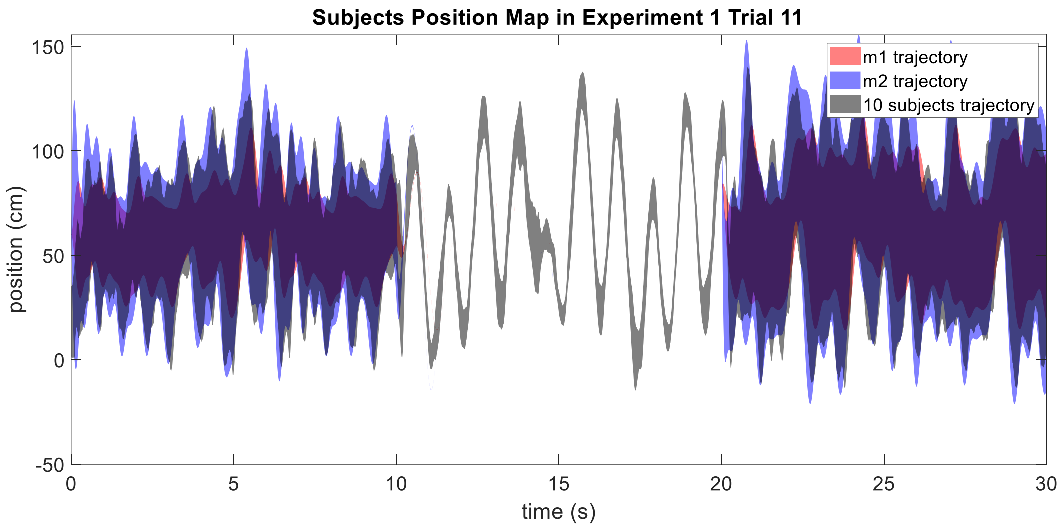

Fig. A.16. Position map of all subjects and masses for trial 11 in experiment 1 retesting 1 day after

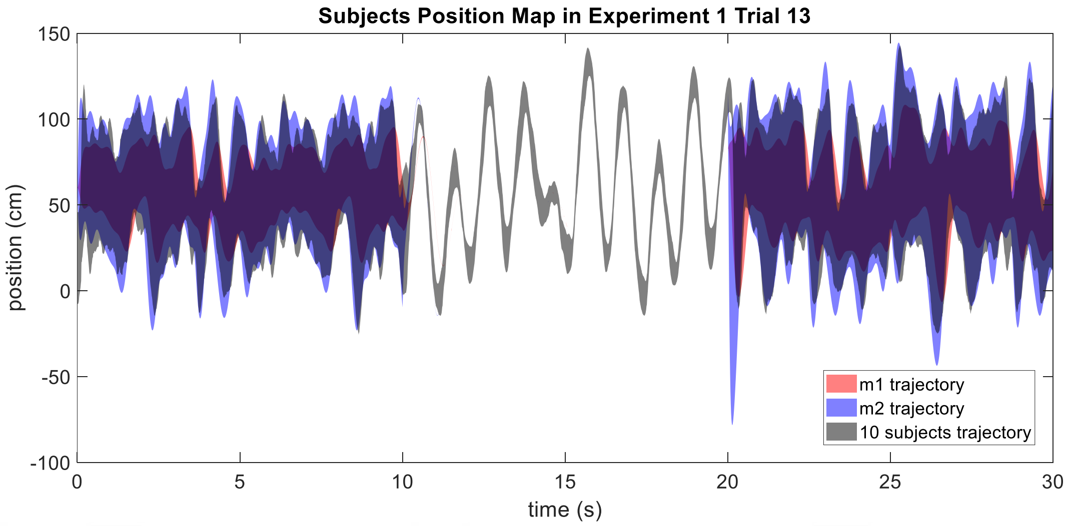

Fig. A.17. Position map of all subjects and masses for trial 13 in experiment 1 retesting 1 day after

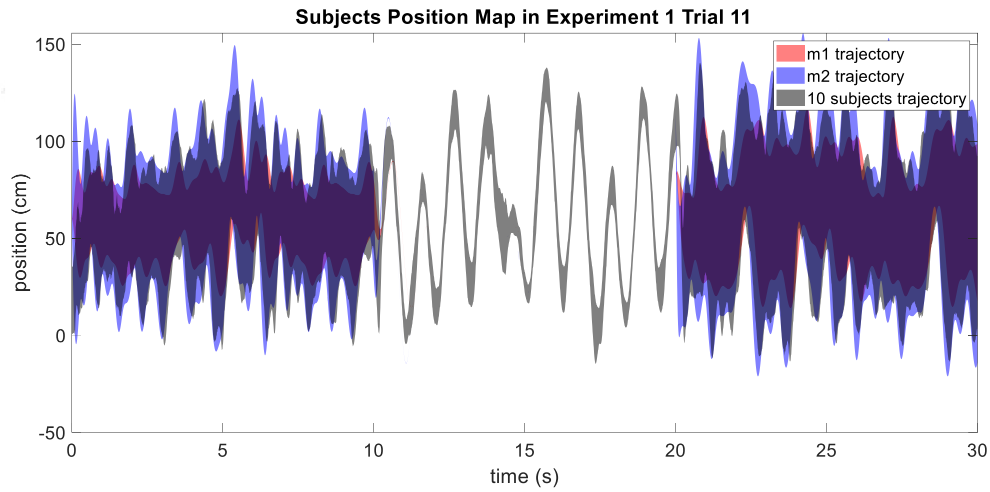

Fig. A.18. Position map of all subjects and masses for trial 11 in experiment 1 retesting 1 week after

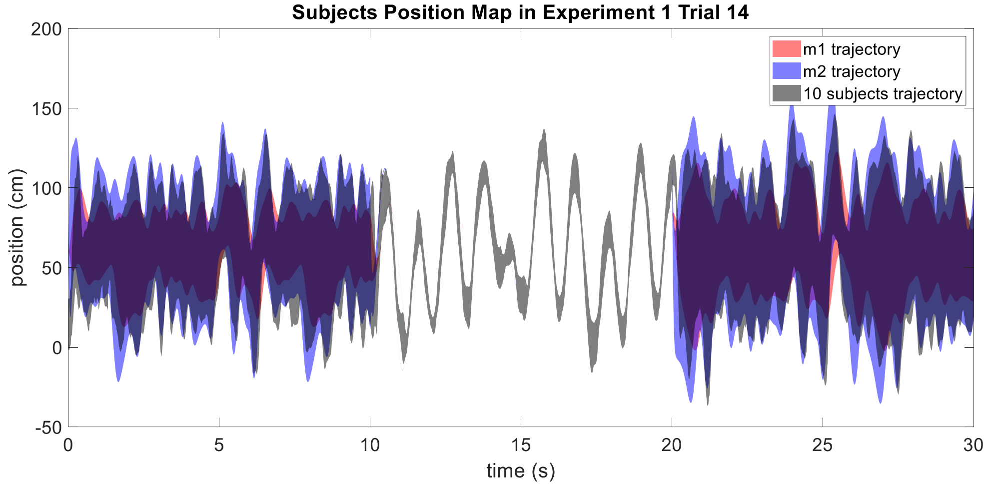

Fig. A.19. Position map of all subjects and masses for trial 14 in experiment 1 retesting 1 week after

Table A.1 ANOVA result between segments for EMD in the experiment 1

Source	SS	df	MS	F	Prob>F
Columns	0.00022	2	0.00011	0.29	0.7513
Error	0.01029	27	0.00038		
Total	0.01051	29			

Table A.2 ANOVA result between segments for RMSE in the experiment 1

Source	SS	df	MS	F	Prob>F
Columns	2.77229	2	1.38615	26.17	$4.78984e^{-7}$
Error	1.43013	27	0.05297		
Total	4.20242	29			

Table A.3 ANOVA result between segments for CV in the experiment 1

Source	SS	df	MS	F	Prob>F
Columns	0.01156	2	0.00578	8.3	0.0016
Error	0.01881	27	0.0007		
Total	0.03037	29			

Table A.4 ANOVA result between segments for SL in the experiment 1

Source	SS	df	MS	F	Prob>F
Columns	0.03622	2	0.01811	56.6	$5.22128e^{-10}$
Error	0.008	25	0.00032		
Total	0.04422	27			

Table A.5 ANOVA result between segments for entropy in the experiment 1

Source	SS	df	MS	F	Prob>F
Columns	0.27069	2	0.13535	11.24	0.0003
Error	0.32506	27	0.01204		
Total	0.59575	29			

Table A.6 Metric analysis for 10 subjects in trial 11 and 12 to test transfer of IL in the experiment 1

Subject Number	Trial 11	Trial 12	Metric Orders	Subject Number	Trial 11	Trial 12
Subject 1	0.037	0.065	EMD	**Subject 6**	0.019	0.091
	1.245	1.559	RMSE		1.174	1.868
	0.017	0.025	SL		0.031	0.048
	0.936	0.915	CV		0.916	0.885
	3.484	3.696	SE		3.766	3.834
Subject 2	0.031	0.032	EMD	**Subject 7**	0.014	0.021
	0.996	1.230	RMSE		1.013	1.079
	0.056	0.034	SL		0.008	0.041
	0.971	0.856	CV		0.959	0.964
	3.174	3.694	SE		3.692	3.764
Subject 3	0.011	0.038	EMD	**Subject 8**	0.0488	0.027
	1.131	1.323	RMSE		1.204	1.490
	0.021	0.018	SL		0.056	0.048
	0.963	0.911	CV		0.917	0.894
	3.666	3.637	SE		3.574	3.630
Subject 4	0.021	0.051	EMD	**Subject 9**	0.093	0.009
	1.485	2.111	RMSE		1.801	2.217
	0.054	0.017	SL		0.024	0.076
	0.934	0.915	CV		0.848	0.906
	3.646	3.589	SE		3.317	3.901
Subject 5	0.028	0.077	EMD	**Subject 10**	0.011	0.026
	1.475	1.546	RMSE		1.140	1.251
	0.142	0.023	SL		0.050	0.038
	0.929	0.883	CV		0.923	0.960
	3.702	3.437	SE		3.780	3.770

Table A.7 Metric analysis for 10 subjects in trial 11 and 13 to test durability of IL after 1 day in the experiment 1

Subject Number	**Trial 11**	**Trial 13**	**Metric Orders**	**Subject Number**	**Trial 11**	**Trial 13**
Subject 1	0.037 1.245 0.017 0.936 3.484	0.014 0.618 0.028 0.977 3.758	EMD RMSE SL CV SE	**Subject 6**	0.019 1.174 0.031 0.916 3.766	0.012 1.309 0.127 0.919 3.806
Subject 2	0.031 0.996 0.056 0.971 3.174	0.016 0.860 0.005 0.824 3.761	EMD RMSE SL CV SE	**Subject 7**	0.014 1.013 0.008 0.959 3.692	0.011 0.673 0.011 0.978 3.829
Subject 3	0.011 1.131 0.021 0.963 3.666	0.032 1.178 0.045 0.945 3.699	EMD RMSE SL CV SE	**Subject 8**	0.0488 1.204 0.056 0.917 3.574	0.015 1.159 0.044 0.922 3.826
Subject 4	0.021 1.485 0.054 0.934 3.646	0.010 1.090 0.022 0.954 3.699	EMD RMSE SL CV SE	**Subject 9**	0.093 1.801 0.024 0.848 3.317	0.079 1.612 0.092 0.878 3.419
Subject 5	0.028 1.475 0.142 0.929 3.702	0.016 1.107 0.023 0.954 3.913	EMD RMSE SL CV SE	**Subject 10**	0.011 1.140 0.050 0.923 3.780	0.038 1.354 0.024 0.907 3.696

Table A.8 Metric analysis for 10 subjects in trial 11 and 14 to test durability of IL after 1 week in the experiment 1

Subject Number	Trial 11	Trial 14	Metric Orders	Subject Number	Trial 11	Trial 14
Subject 1	0.037 1.245 0.017 0.936 3.484	0.022 1.829 0.046 0.902 3.810	EMD RMSE SL CV SE	**Subject 6**	0.019 1.174 0.031 0.916 3.766	0.033 0.996 0.012 0.953 3.652
Subject 2	0.031 0.996 0.056 0.971 3.174	0.027 1.034 0.021 0.963 3.684	EMD RMSE SL CV SE	**Subject 7**	0.014 1.013 0.008 0.959 3.692	0.024 0.925 0.041 0.954 3.749
Subject 3	0.011 1.131 0.021 0.963 3.666	0.023 1.525 0.051 0.933 3.985	EMD RMSE SL CV SE	**Subject 8**	0.0488 1.204 0.056 0.917 3.574	0.115 2.509 0.034 0.797 3.473
Subject 4	0.021 1.485 0.054 0.934 3.646	0.038 0.933 0.034 0.928 3.639	EMD RMSE SL CV SE	**Subject 9**	0.093 1.801 0.024 0.848 3.317	0.022 0.885 0.051 0.964 3.785
Subject 5	0.028 1.475 0.142 0.929 3.702	0.026 1.182 0.022 0.978 3.729	EMD RMSE SL CV SE	**Subject 10**	0.011 1.140 0.050 0.923 3.780	0.016 1.059 0.022 0.948 3.769

B. Experiment 2 (HI+) Results

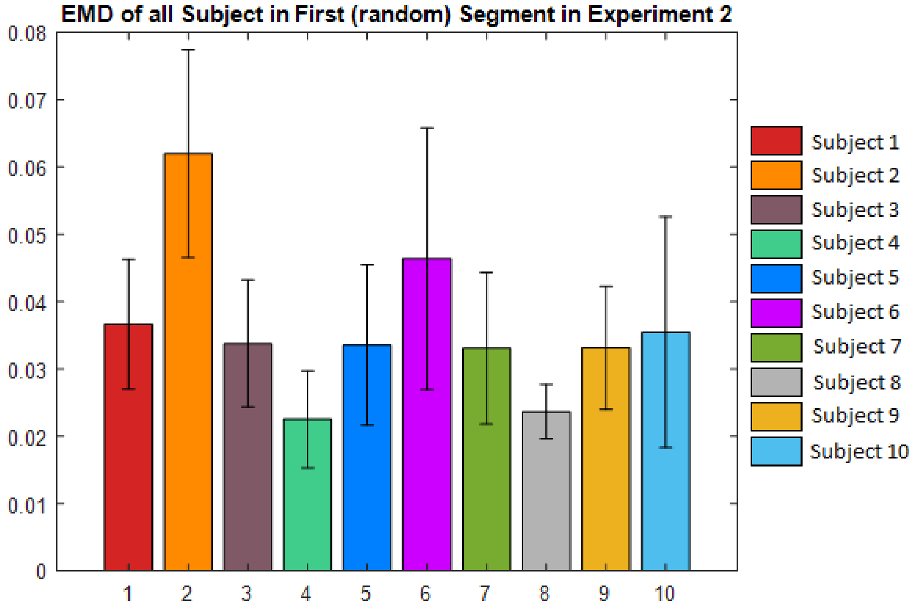

Fig. B.1. EMD of 10 subjects in first segment of the experiment 2

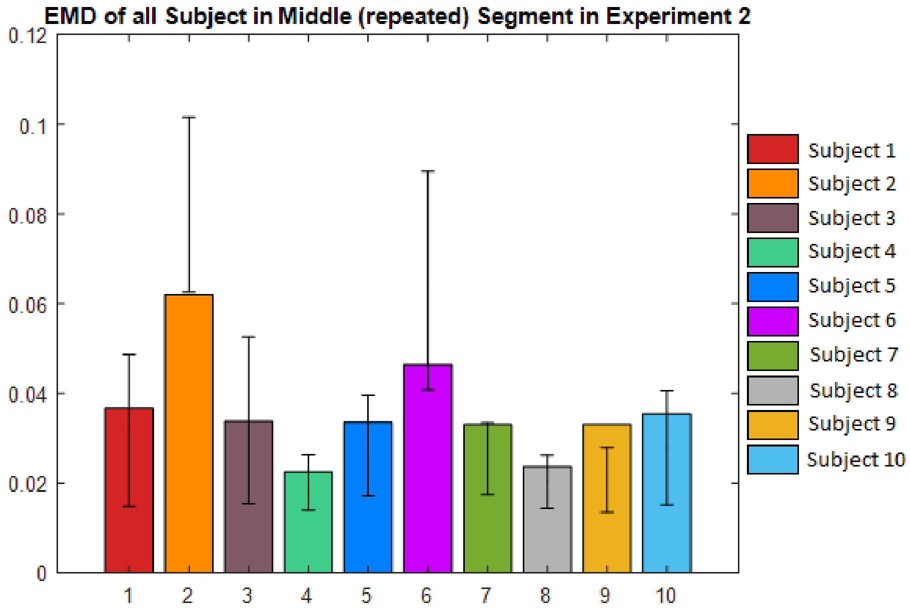

Fig. B.2. EMD of 10 subjects in middle segment of the experiment 2

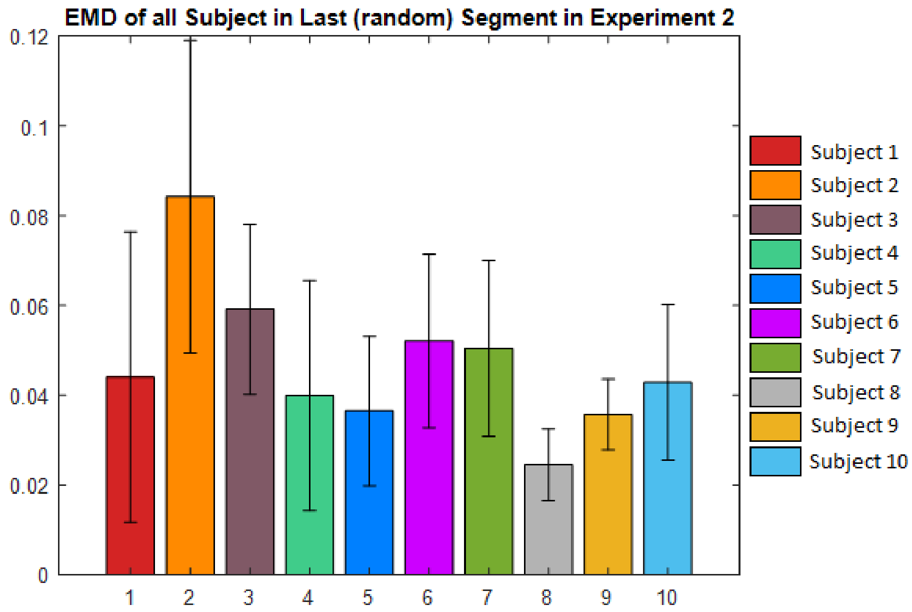

Fig. B.3. EMD of 10 subjects in last segment of the experiment 2

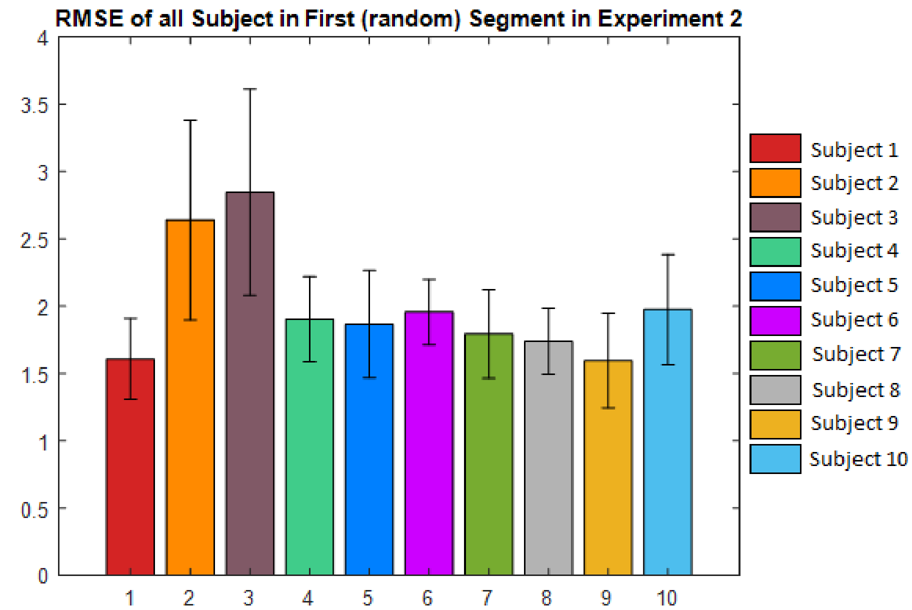

Fig. B.4. RMSE of 10 subjects in first segment of the experiment 2

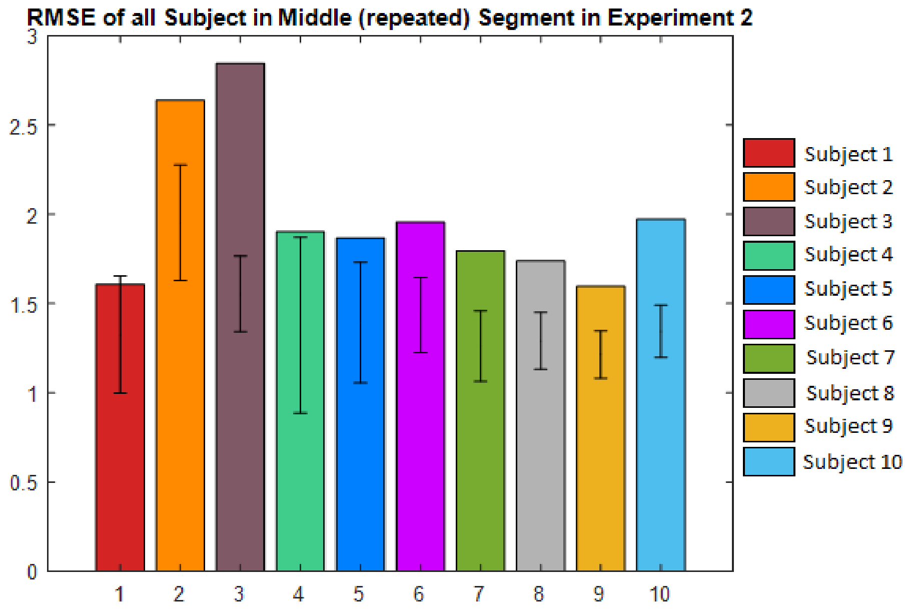

Fig. B.5. RMSE of 10 subjects in middle segment of the experiment 2

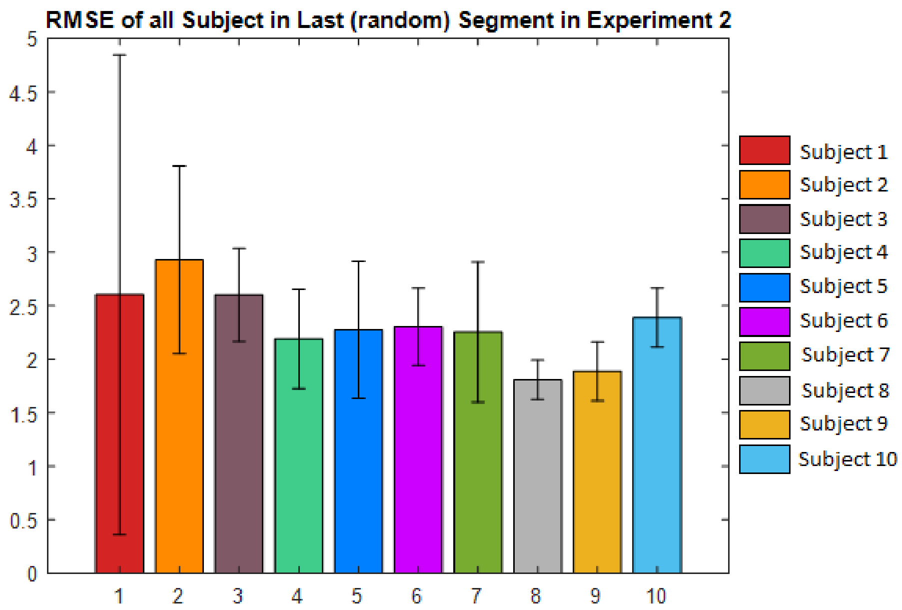

Fig. B.6. RMSE of 10 subjects in last segment of the experiment 2

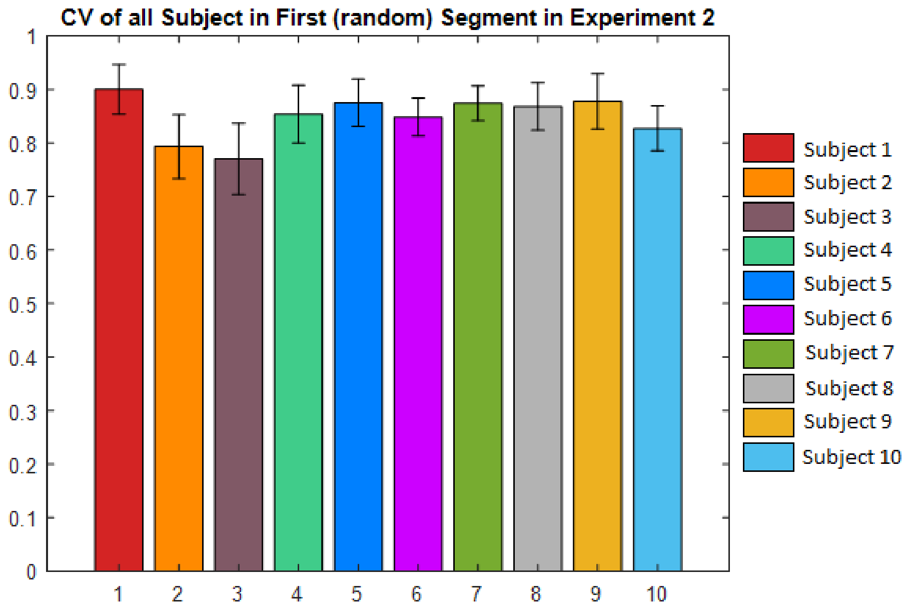

Fig. B.7. CV of 10 subjects in first segment of the experiment 2

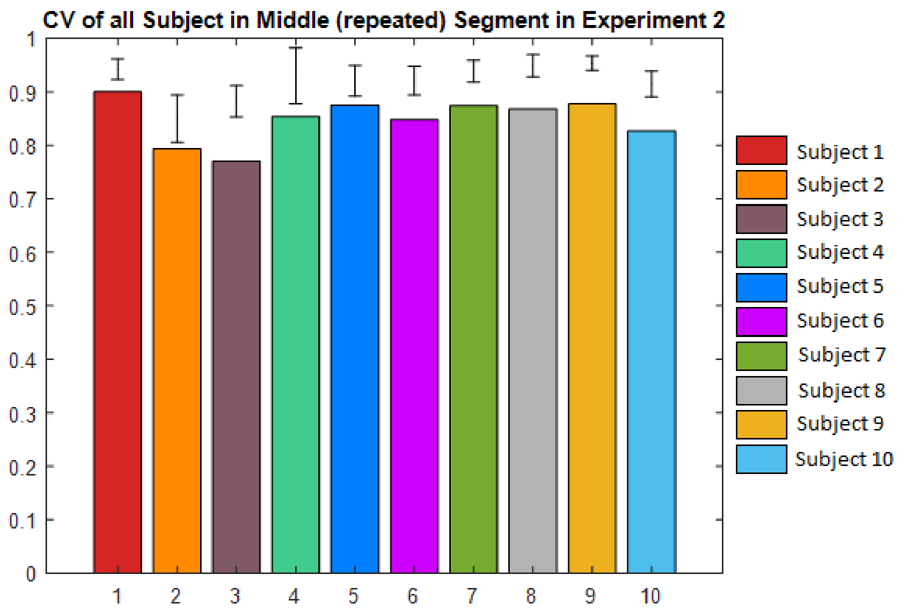

Fig. B.8. CV of 10 subjects in middle segment of the experiment 2

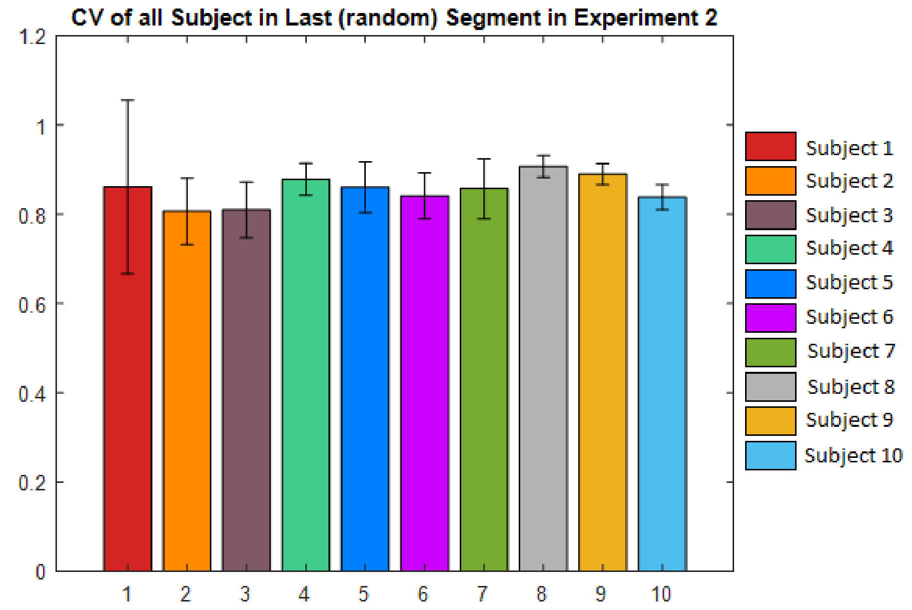

Fig. B.9. CV of 10 subjects in last segment of the experiment 2

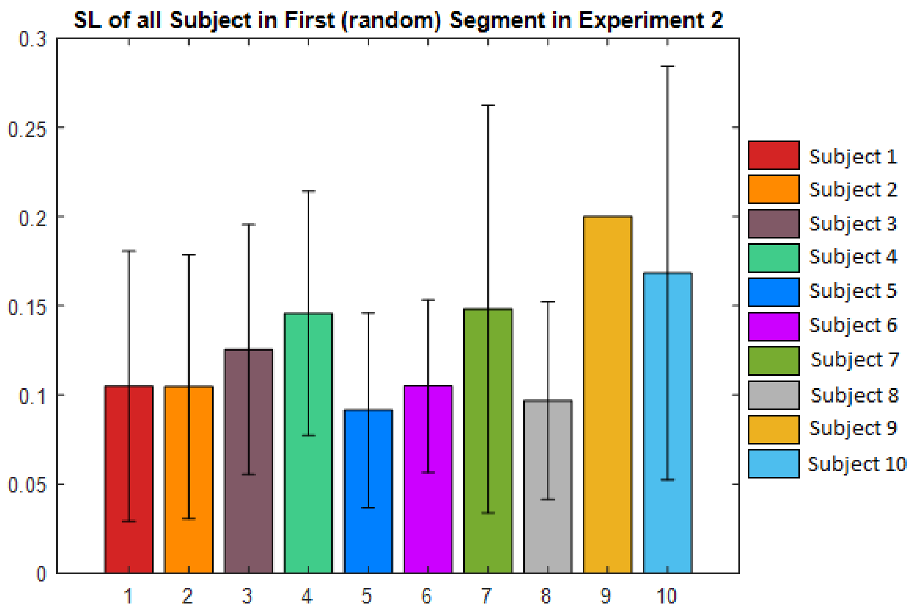

Fig. B.10. SL of 10 subjects in first segment of the experiment 2

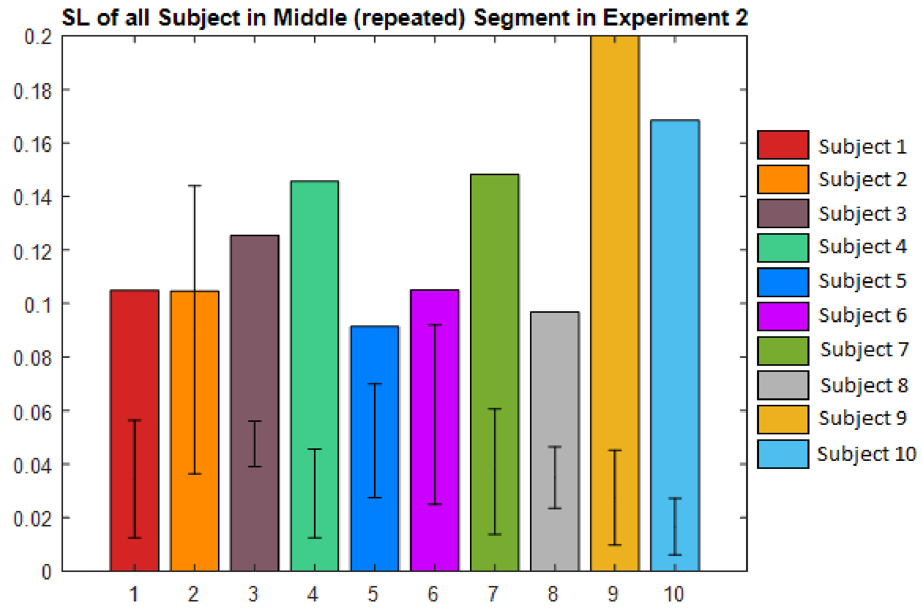

Fig. B.11. SL of 10 subjects in middle segment of the experiment 2

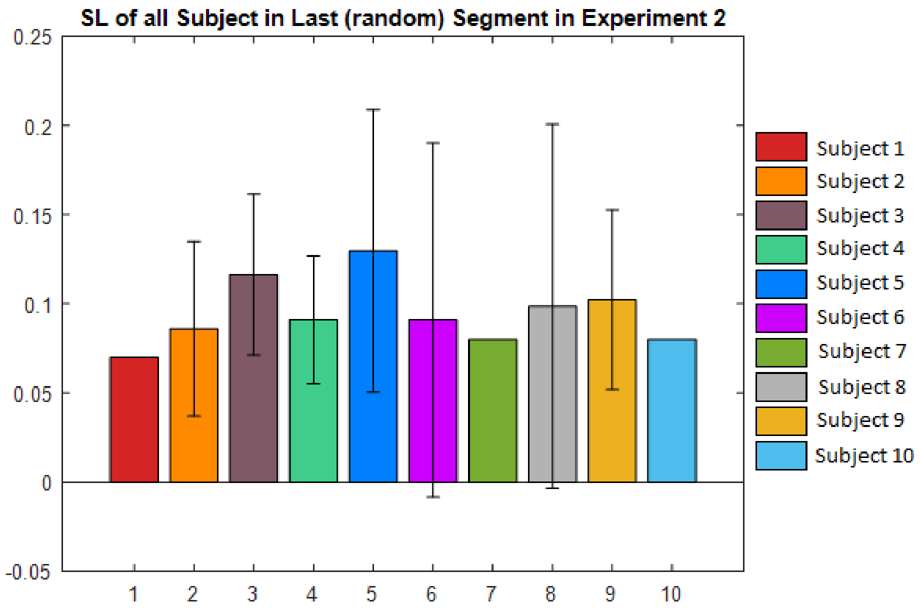

Fig. B.12. SL of 10 subjects in last segment of the experiment 2

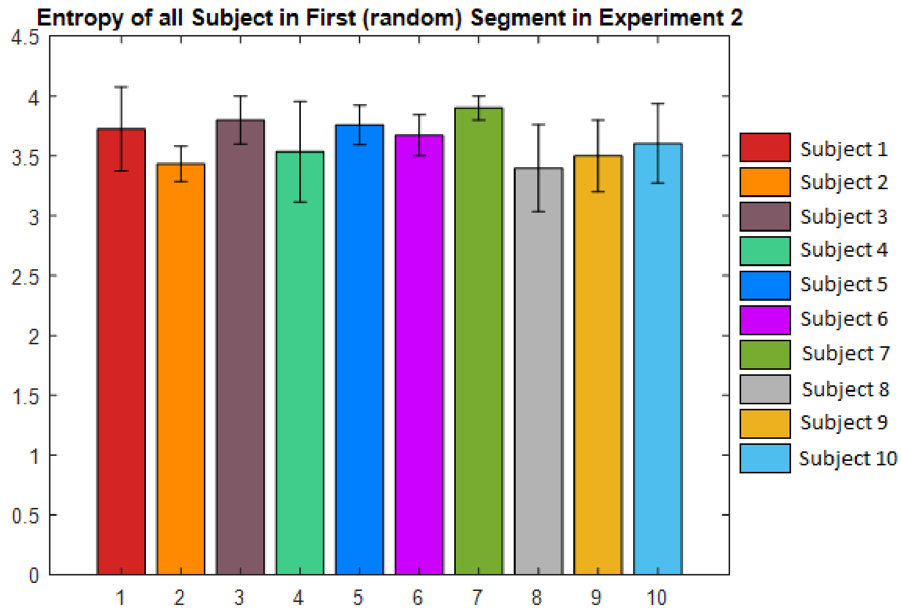

Fig. B.13. Entropy of 10 subjects in first segment of the experiment 2

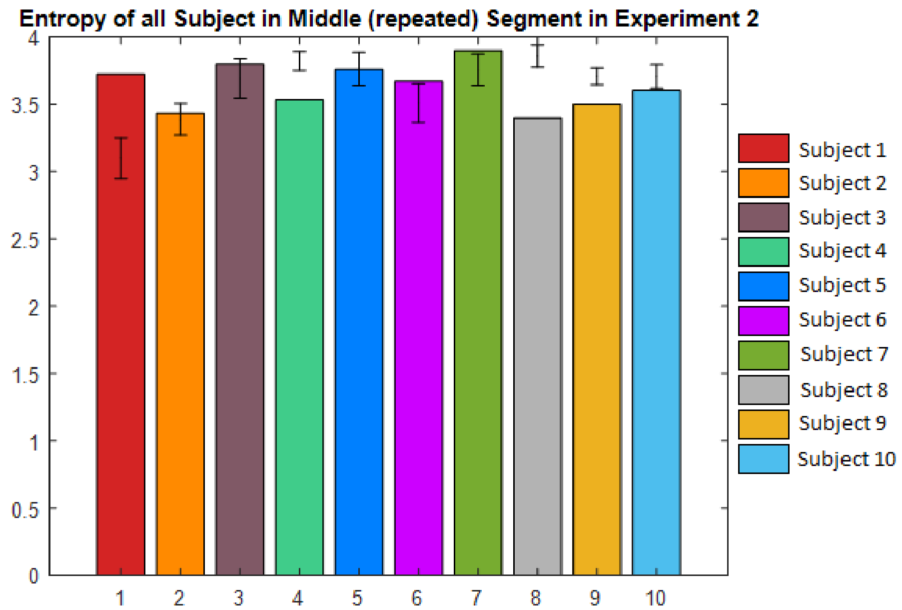

Fig. B.14. Entropy of 10 subjects in middle segment of the experiment 2

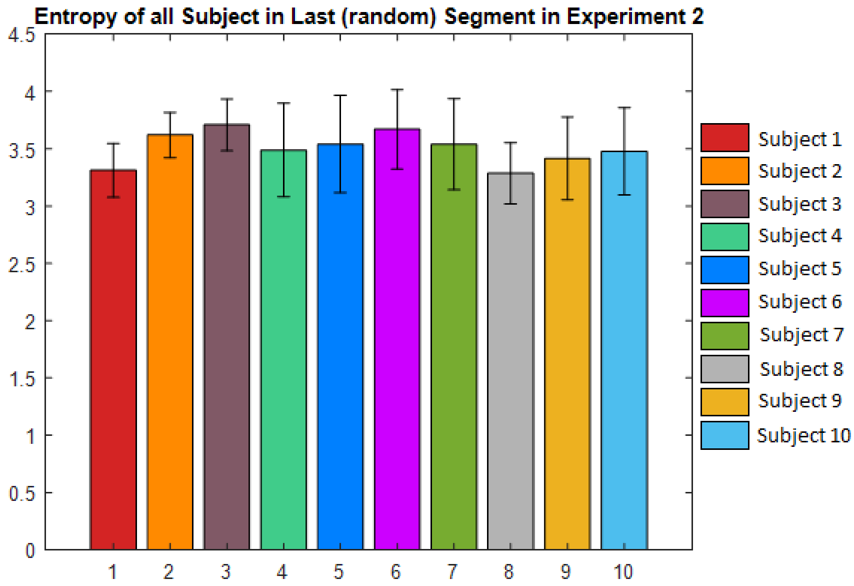

Fig. B.15. Entropy of 10 subjects in last segment of the experiment 2

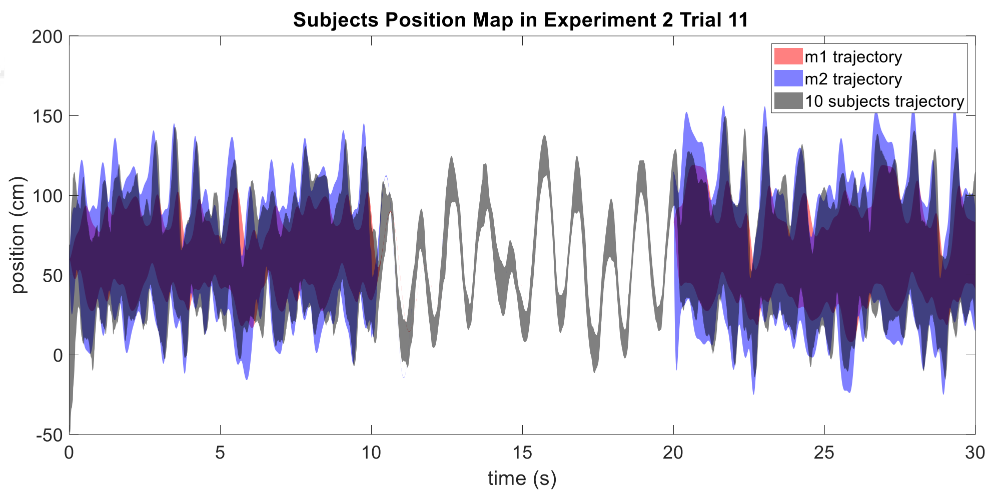

Fig. B.16. Position map of all subjects and masses for trial 11 in experiment 2

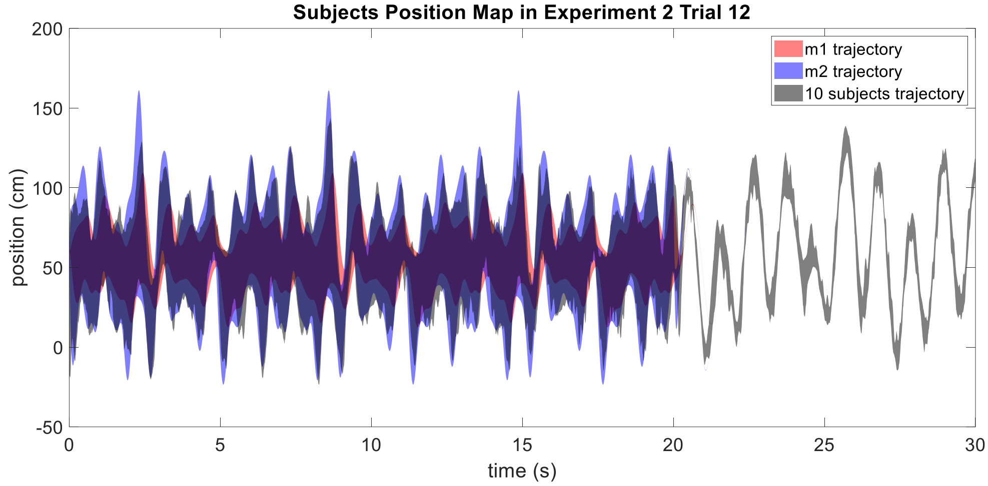

Fig. B.17. Position map of all subjects and masses for trial 12 in experiment 2

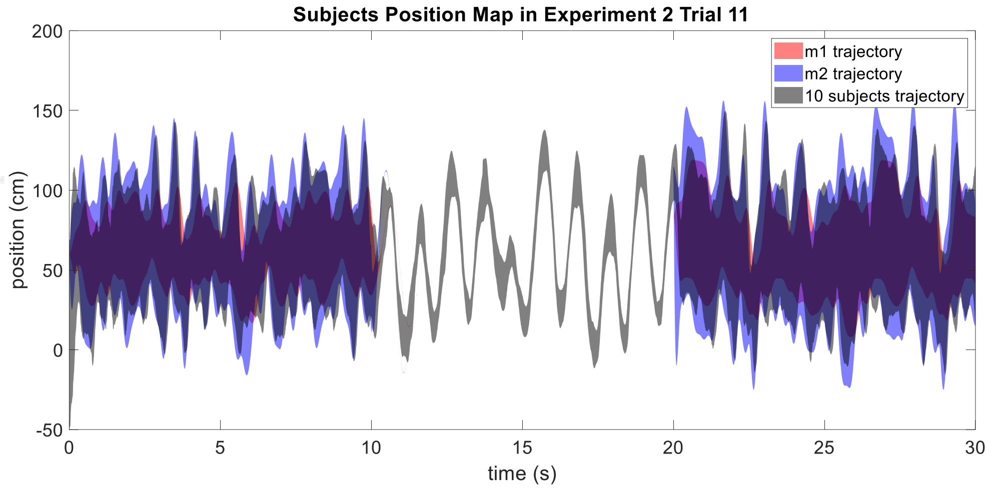

Fig. B.18. Position map of all subjects and masses for trial 11 in experiment 2 retesting 1 day after

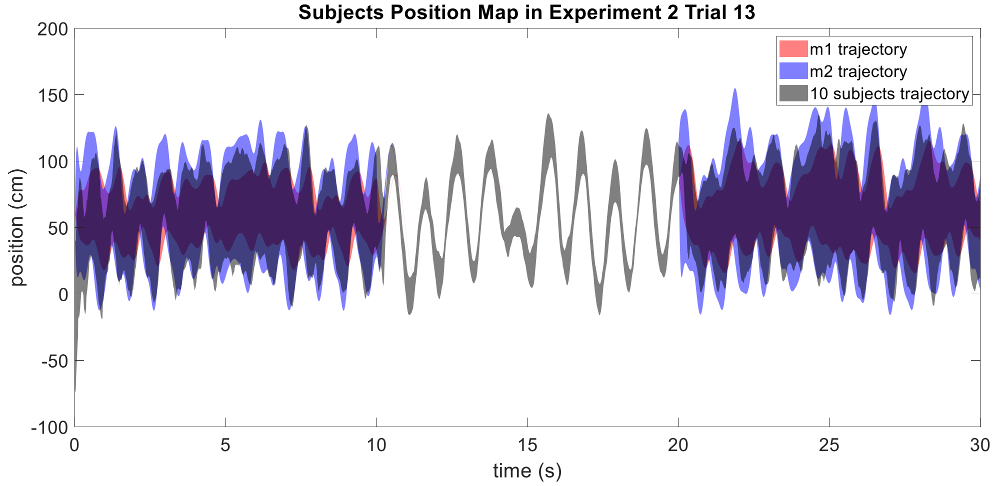

Fig. B.19. Position map of all subjects and masses for trial 13 in experiment 2 retesting 1 day after

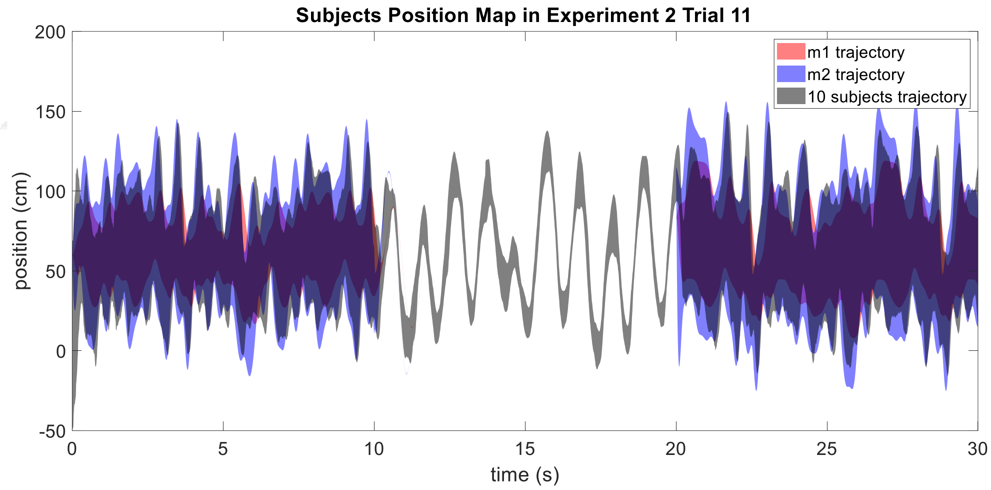

Fig. B.20. Position map of all subjects and masses for trial 11 in experiment 2 retesting 1 week after

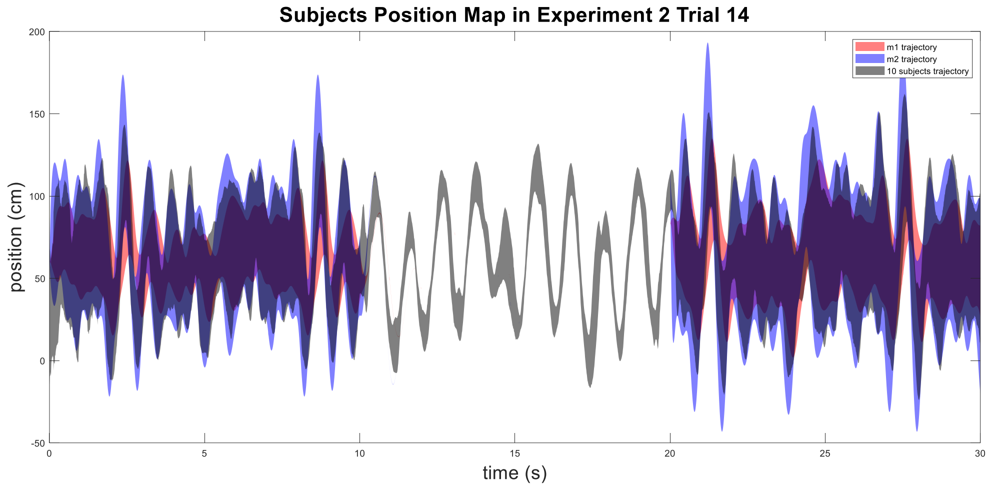

Fig. B.21. Position map of all subjects and masses for trial 14 in experiment 2 retesting 1 week after

Table B.1 ANOVA result between segments for EMD in the experiment 2

Source	SS	df	MS	F	Prob>F
Columns	0.00083	2	0.00041	1.49	0.2425
Error	0.0075	27	0.00028		
Total	0.00833	29			

Table B.2 ANOVA result between segments for RMSE in the experiment 2

Source	SS	df	MS	F	Prob>F
Columns	4.24025	2	2.12013	19.12	$6.72193e^{-6}$
Error	2.99392	27	0.11089		
Total	7.23417	29			

Table B.3 ANOVA result between segments for CV in the experiment 2

Source	SS	df	MS	F	Prob>F
Columns	0.03114	2	0.01557	12.51	0.0001
Error	0.0336	27	0.00124		
Total	0.06474	29			

Table B.4 ANOVA result between segments for SL in the experiment 2

Source	SS	df	MS	F	Prob>F
Columns	0.03186	2	0.01593	32.85	$1.81292e^{-7}$
Error	0.01115	23	0.00048		
Total	0.04302	25			

Table B.5 ANOVA result between segments for entropy in the experiment 2

Source	SS	df	MS	F	Prob>F
Columns	0.16132	2	0.08066	3.91	0.0345
Error	0.47434	23	0.02062		
Total	0.63566	25			

Table B.6 Metric analysis for 10 subjects in trial 11 and 12 to test transfer of IL in the experiment 2

Subject Number	**Trial 11**	**Trial 12**	**Metric Orders**	**Subject Number**	**Trial 11**	**Trial 12**
Subject 1	0.029 1.379 0.018 0.941 3.692	0.014 1.453 0.039 0.943 3.668	EMD RMSE SL CV SE	**Subject 6**	0.063 1.539 0.083 0.898 3.567	0.029 1.606 0.094 0.912 3.737
Subject 2	0.089 2.013 0.029 0.884 3.359	0.023 0.894 0.024 0.961 3.624	EMD RMSE SL CV SE	**Subject 7**	0.024 1.094 0.065 0.943 3.748	0.054 1.885 0.190 0.920 3.987
Subject 3	0.036 1.974 0.054 0.867 3.530	0.038 1.080 0.042 0.931 3.736	EMD RMSE SL CV SE	**Subject 8**	0.011 1.254 0.046 0.931 3.859	0.049 1.359 0.102 0.909 3.694
Subject 4	0.017 1.671 0.031 0.906 3.823	0.009 0.775 0.035 0.974 3.908	EMD RMSE SL CV SE	**Subject 9**	0.022 1.368 0.067 0.943 3.654	0.055 0.952 0.020 0.969 3.575
Subject 5	0.018 1.084 0.019 0.900 3.724	0.039 1.326 0.053 0.934 3.746	EMD RMSE SL CV SE	**Subject 10**	0.026 1.316 0.028 0.931 3.692	0.016 0.972 0.029 0.967 3.526

Table B.7 Metric analysis for 10 subjects in trial 11 and 13 to test durability of IL after 1 day in the experiment 2

Subject Number	Trial 11	Trial 13	Metric Orders	Subject Number	Trial 11	Trial 13
Subject 1	0.029	0.084	EMD	**Subject 6**	0.063	0.060
	1.379	1.776	RMSE		1.539	1.296
	0.018	0.055	SL		0.083	0.035
	0.941	0.934	CV		0.898	0.929
	3.692	3.604	SE		3.567	3.521
Subject 2	0.089	0.122	EMD	**Subject 7**	0.024	0.012
	2.013	2.215	RMSE		1.094	0.945
	0.029	0.031	SL		0.065	0.045
	0.884	0.862	CV		0.943	0.961
	3.359	3.942	SE		3.748	3.761
Subject 3	0.036	0.048	EMD	**Subject 8**	0.011	0.024
	1.974	1.303	RMSE		1.254	1.561
	0.054	0.052	SL		0.046	0.025
	0.867	0.931	CV		0.931	0.945
	3.530	3.633	SE		3.859	3.966
Subject 4	0.017	0.016	EMD	**Subject 9**	0.022	0.013
	1.671	1.245	RMSE		1.368	1.785
	0.031	0.011	SL		0.067	0.020
	0.906	0.947	CV		0.943	0.915
	3.823	3.687	SE		3.654	3.809
Subject 5	0.018	0.029	EMD	**Subject 10**	0.026	0.023
	1.084	1.336	RMSE		1.316	1.536
	0.019	0.027	SL		0.028	0.051
	0.900	0.909	CV		0.931	0.934
	3.724	3.757	SE		3.692	3.668

Table B.8 Metric analysis for 10 subjects in trial 11 and 14 to test durability of IL after 1 week in the experiment 2

Subject Number	Trial 11	Trial 14	Metric Orders	Subject Number	Trial 11	Trial 14
Subject 1	0.029 1.379 0.018 0.941 3.692	0.066 1.715 0.041 0.892 3.534	EMD RMSE SL CV SE	**Subject 6**	0.063 1.539 0.083 0.898 3.567	0.034 0.951 0.042 0.944 3.643
Subject 2	0.089 2.013 0.029 0.884 3.359	0.070 1.743 0.025 0.851 3.488	EMD RMSE SL CV SE	**Subject 7**	0.024 1.094 0.065 0.943 3.748	0.036 1.286 0.041 0.920 3.658
Subject 3	0.036 1.974 0.054 0.867 3.530	0.047 1.816 0.081 0.877 3.608	EMD RMSE SL CV SE	**Subject 8**	0.011 1.254 0.046 0.931 3.859	0.017 1.107 0.049 0.956 3.735
Subject 4	0.017 1.671 0.031 0.906 3.823	0.022 1.201 0.057 0.930 3.708	EMD RMSE SL CV SE	**Subject 9**	0.022 1.368 0.067 0.943 3.654	0.018 1.101 0.052 0.964 3.728
Subject 5	0.018 1.084 0.019 0.900 3.724	0.029 1.326 0.085 0.940 3.622	EMD RMSE SL CV SE	**Subject 10**	0.026 1.316 0.028 0.931 3.692	0.047 0.978 0.039 0.969 3.603

C. Experiment 3 (HI-) Results

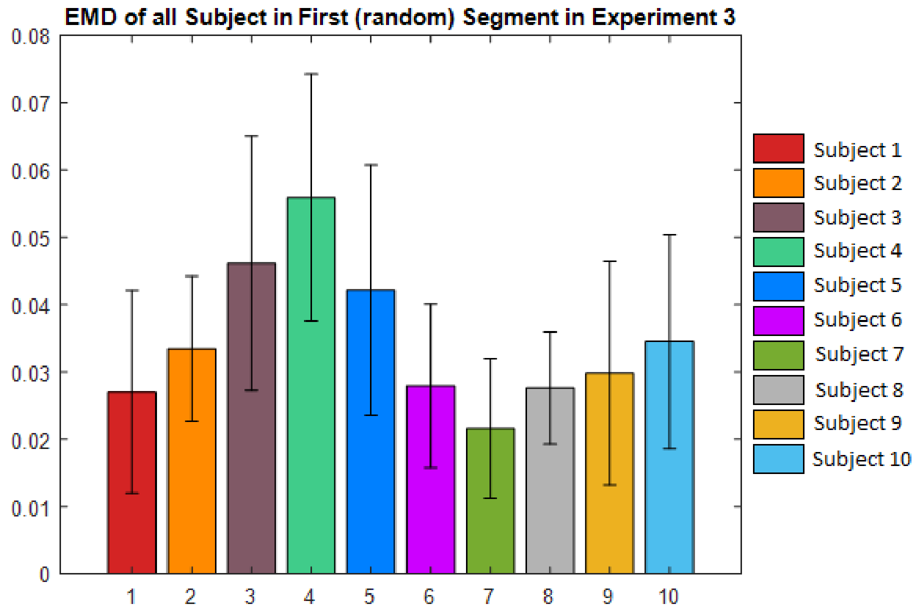

Fig. C.1. EMD of 10 subjects in first segment of the experiment 3

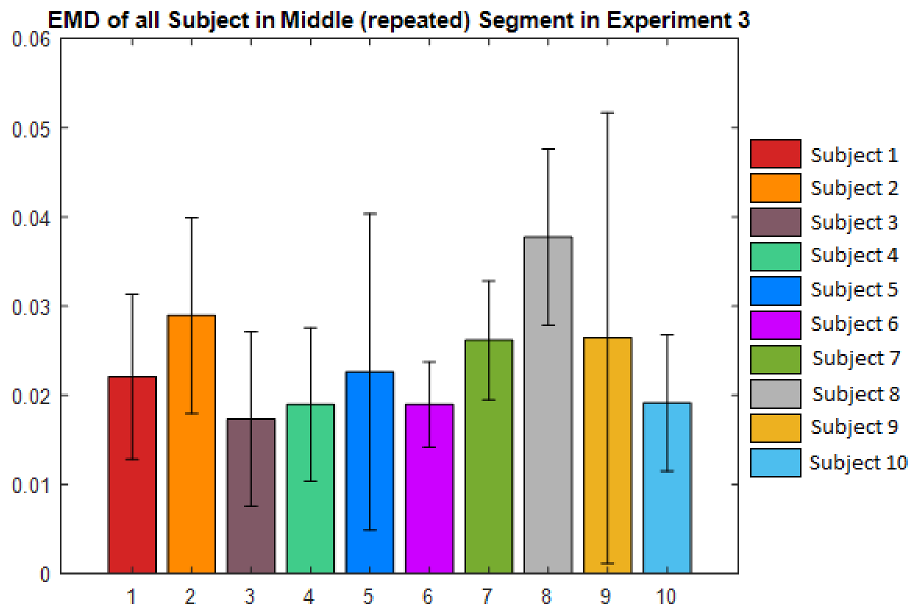

Fig. C.2. EMD of 10 subjects in middle segment of the experiment 3

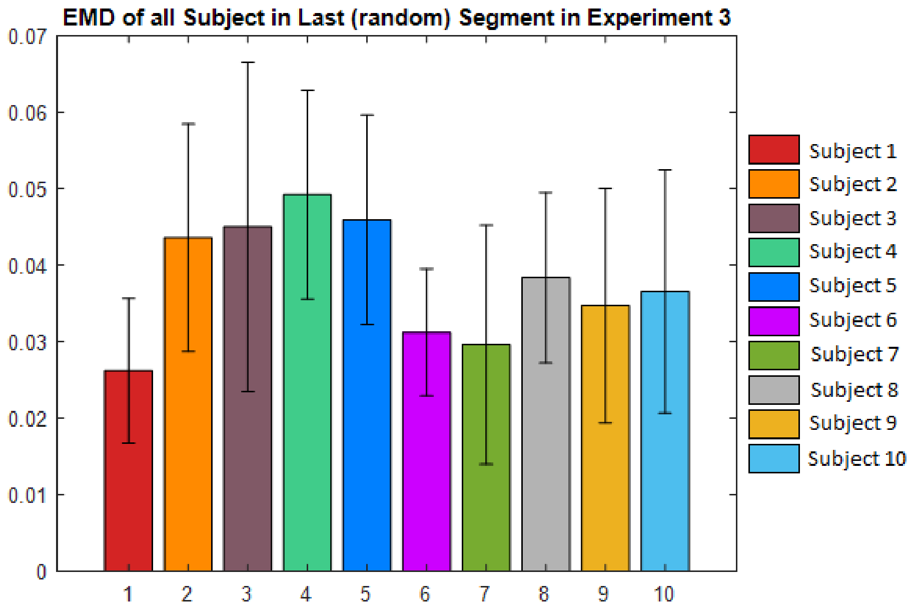

Fig. C.3. EMD of 10 subjects in last segment of the experiment 3

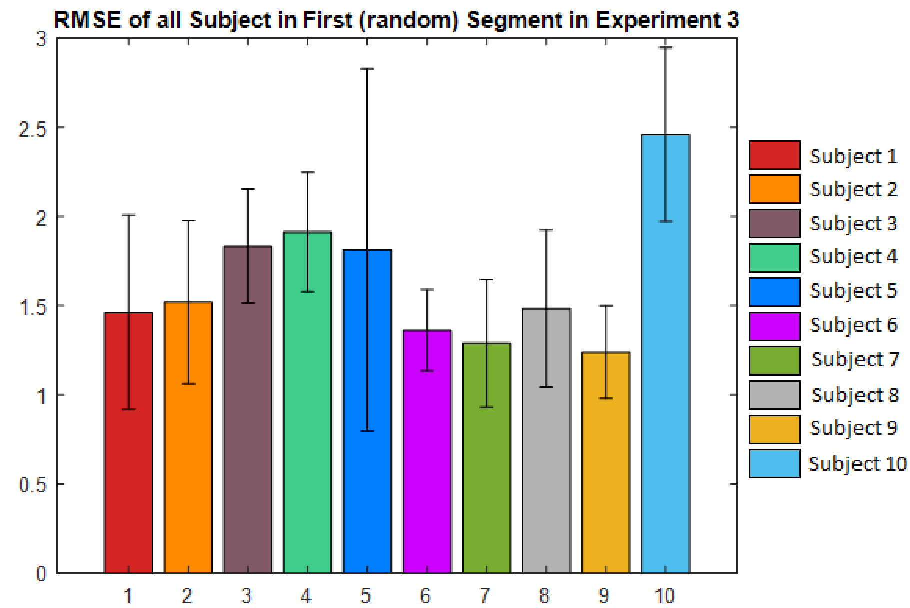

Fig. C.4. RMSE of 10 subjects in first segment of the experiment 3

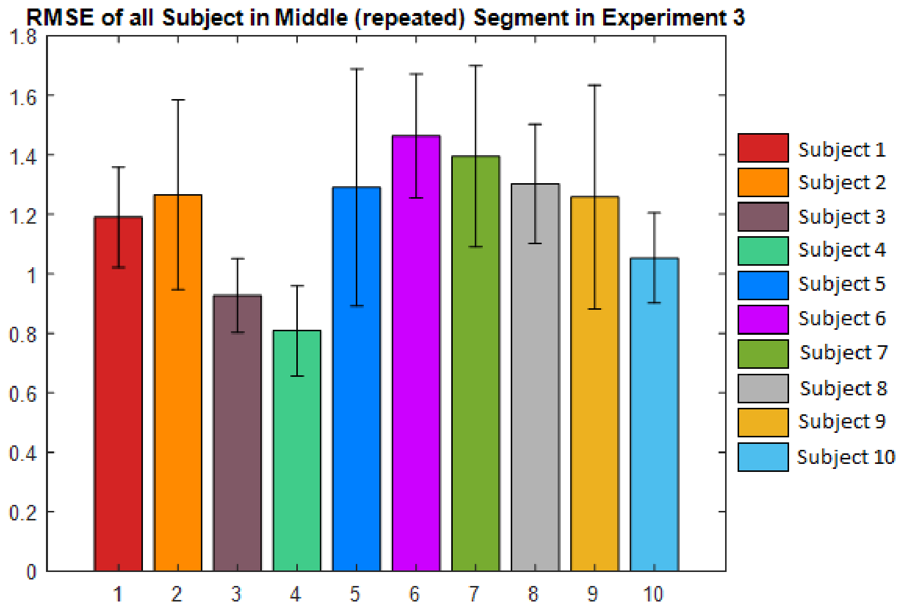

Fig. C.5. RMSE of 10 subjects in middle segment of the experiment 3

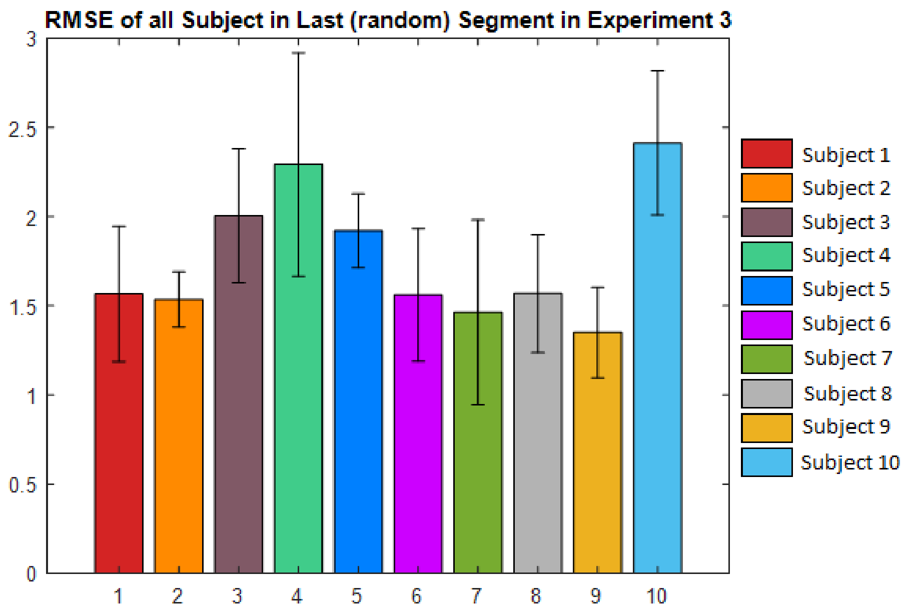

Fig. C.6. RMSE of 10 subjects in last segment of the experiment 3

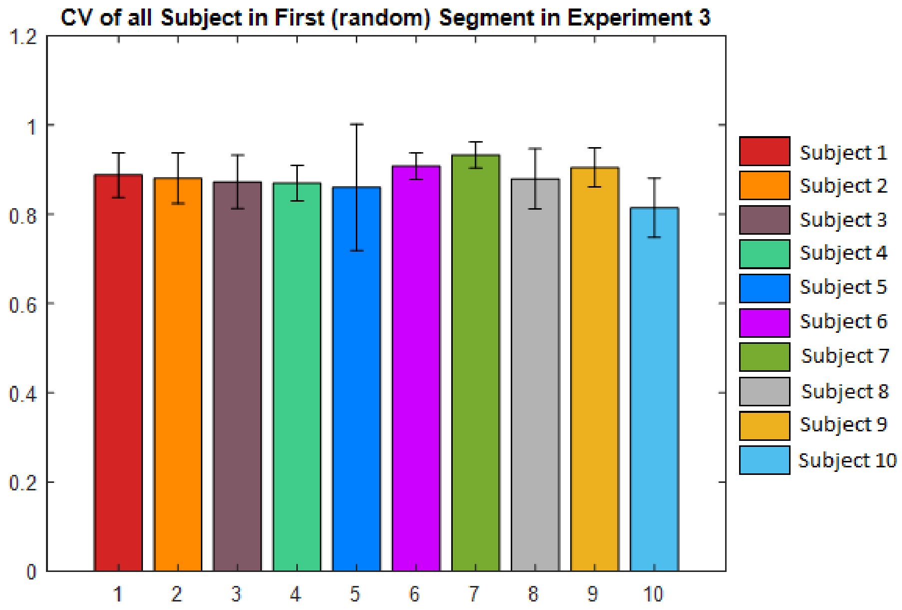

Fig. C.7. CV of 10 subjects in first segment of the experiment 3

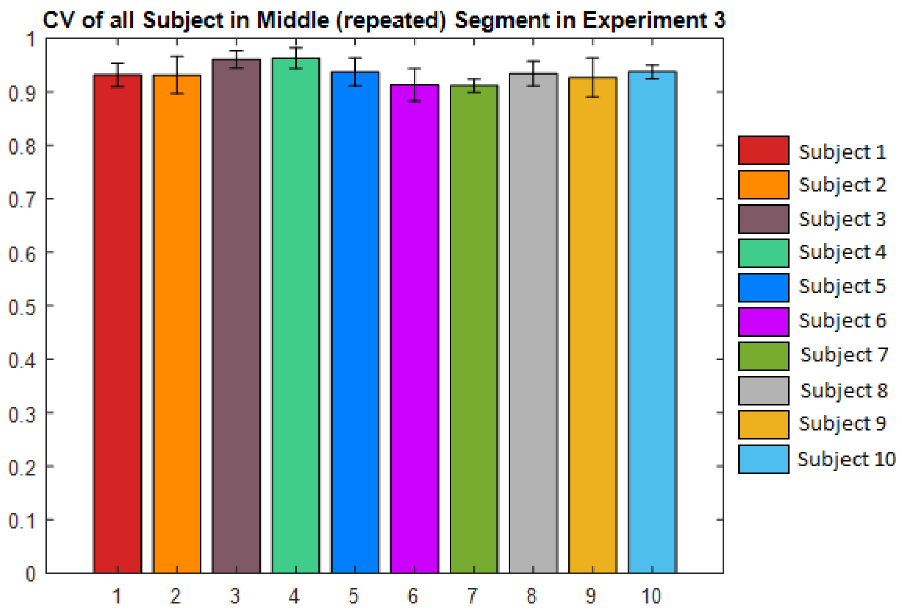

Fig. C.8. CV of 10 subjects in middle segment of the experiment 3

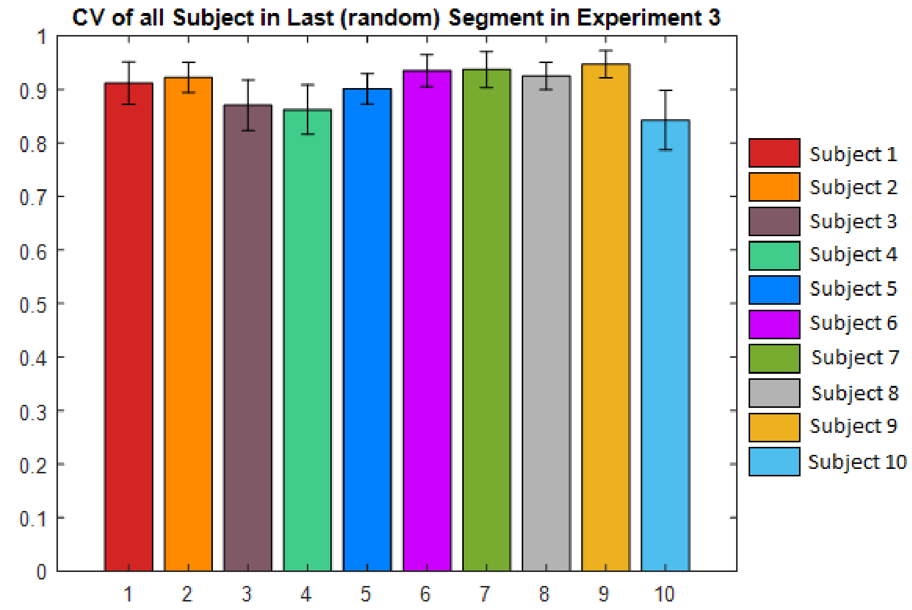

Fig. C.9. CV of 10 subjects in last segment of the experiment 3

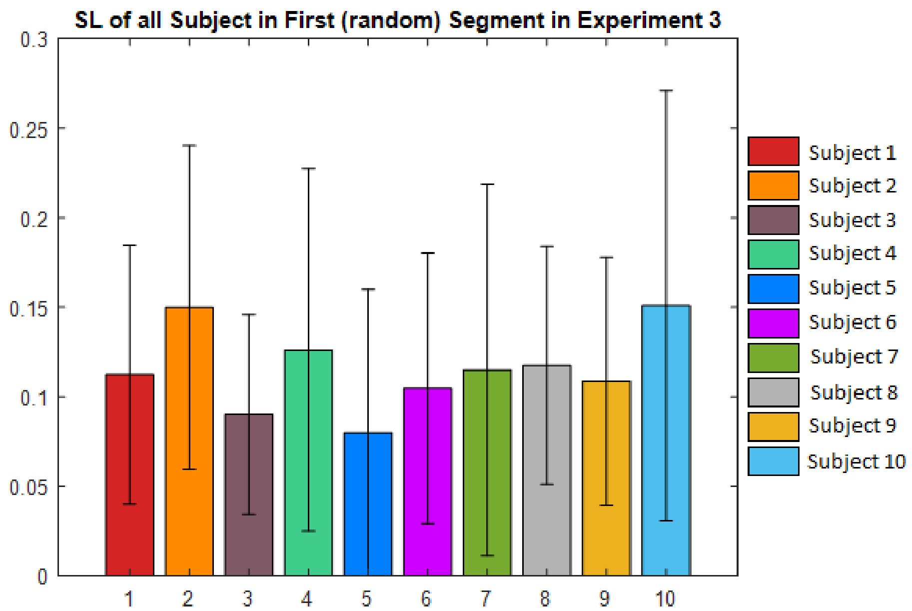

Fig. C.10. SL of 10 subjects in first segment of the experiment 3

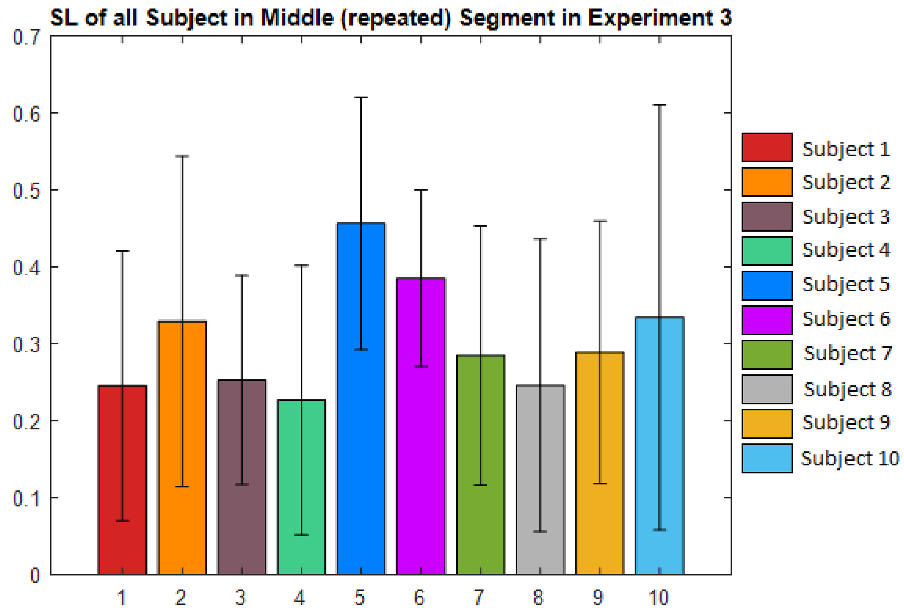

Fig. C.11. SL of 10 subjects in middle segment of the experiment 3

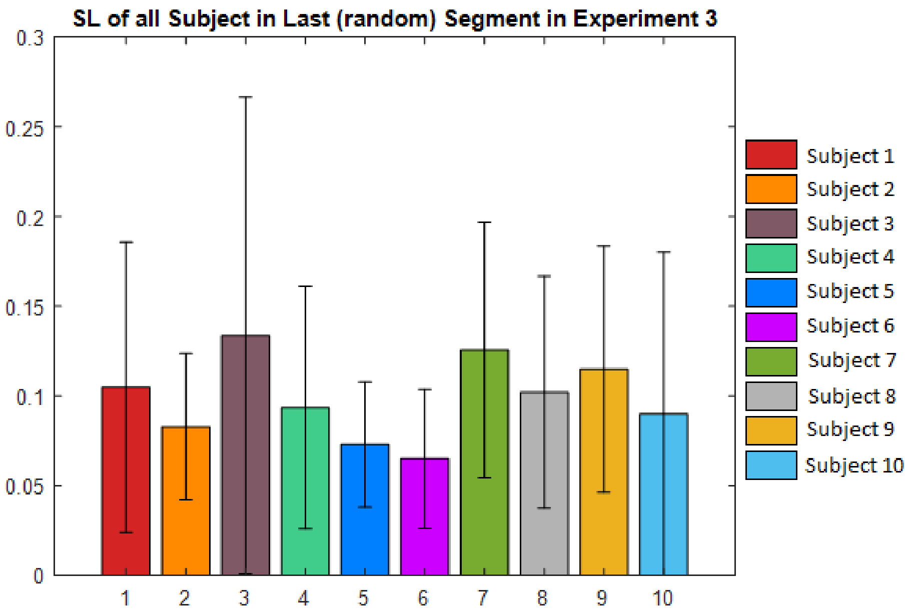

Fig. C.12. SL of 10 subjects in last segment of the experiment 3

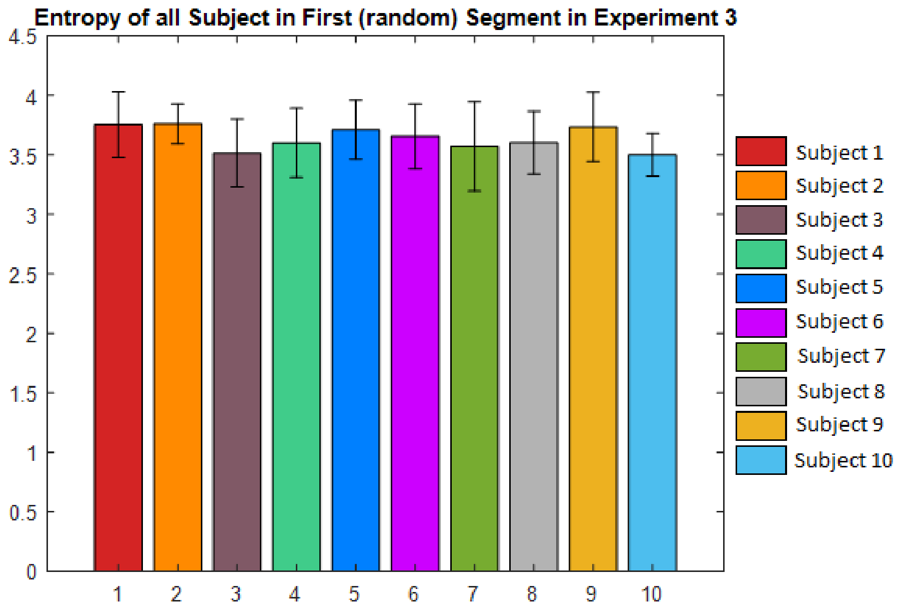

Fig. C.13. Entropy of 10 subjects in first segment of the experiment 3

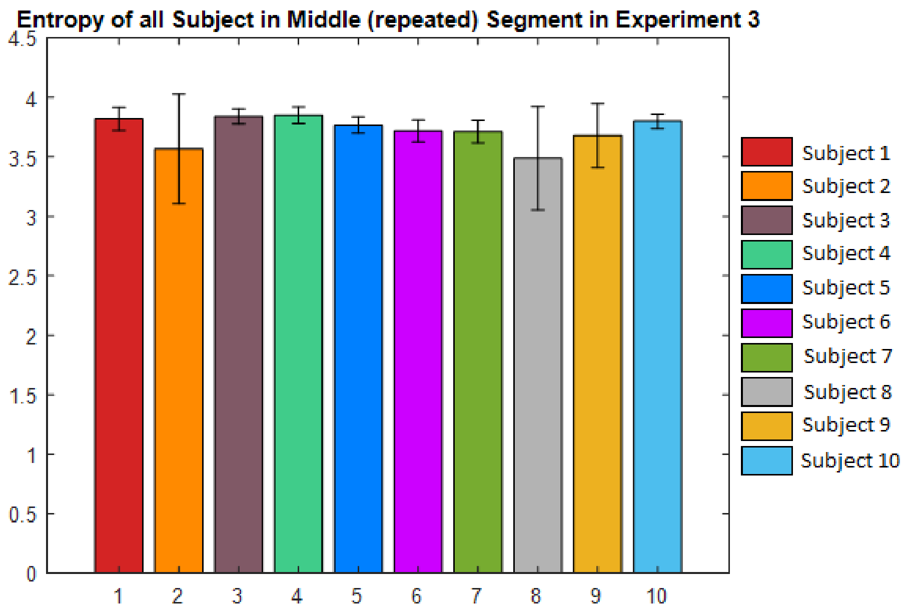

Fig. C.14. Entropy of 10 subjects in middle segment of the experiment 3

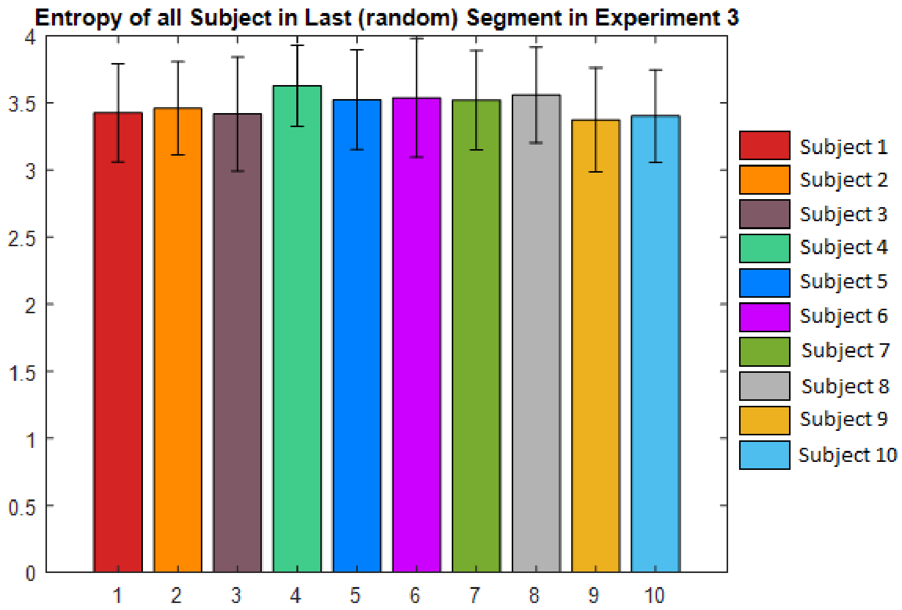

Fig. C.15. Entropy of 10 subjects in last segment of the experiment 3

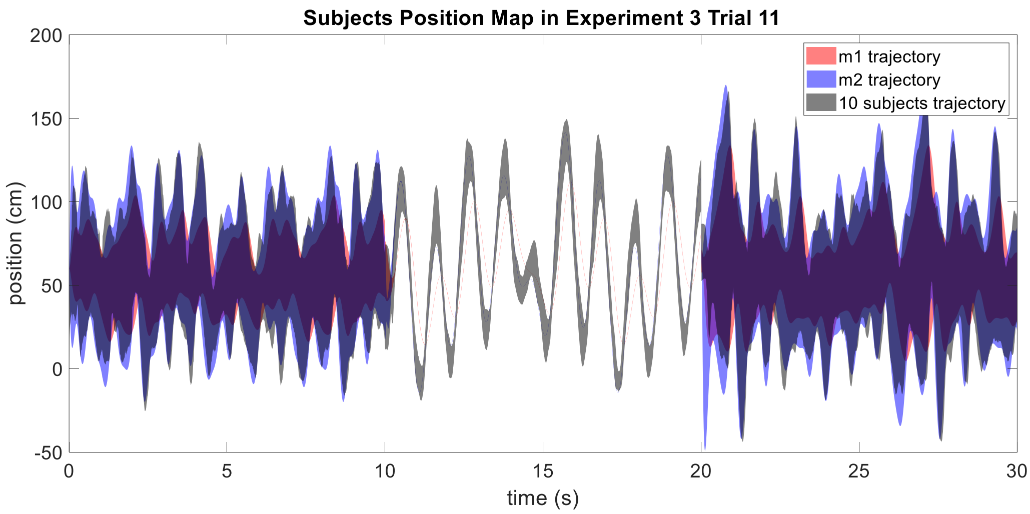

Fig. C.16. Position map of all subjects and masses for trial 11 in experiment 3

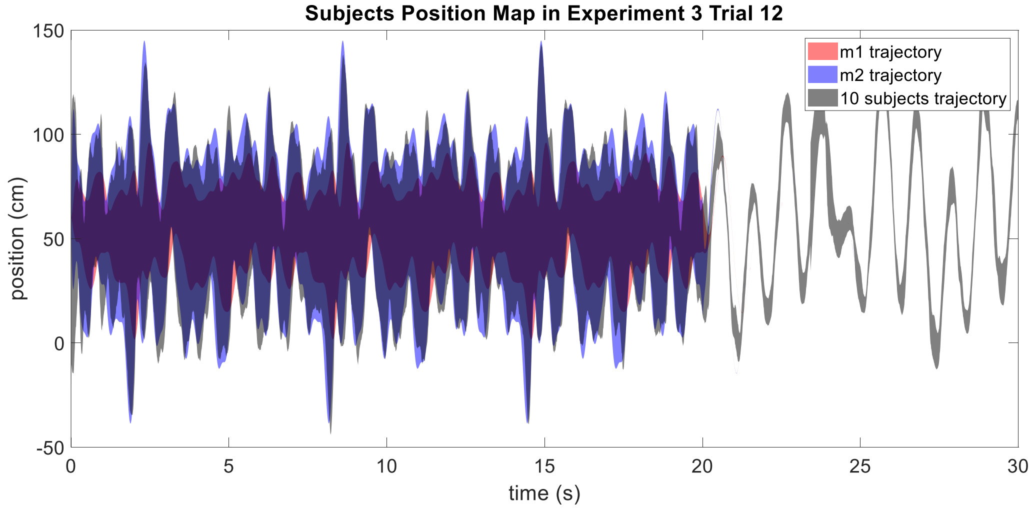

Fig. C.17. Position map of all subjects and masses for trial 12 in experiment 3

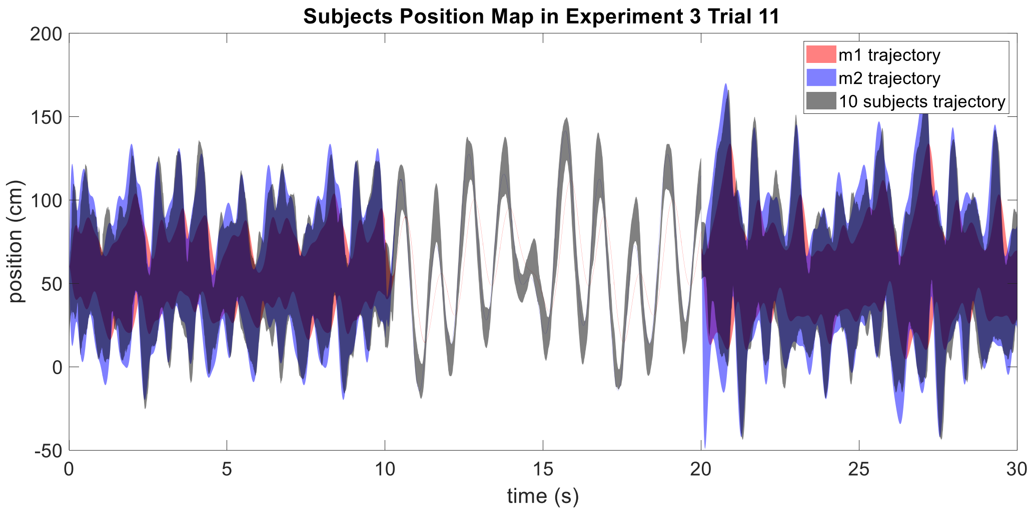

Fig. C.18. Position map of all subjects and masses for trial 11 in the experiment 3 retesting 1 day after

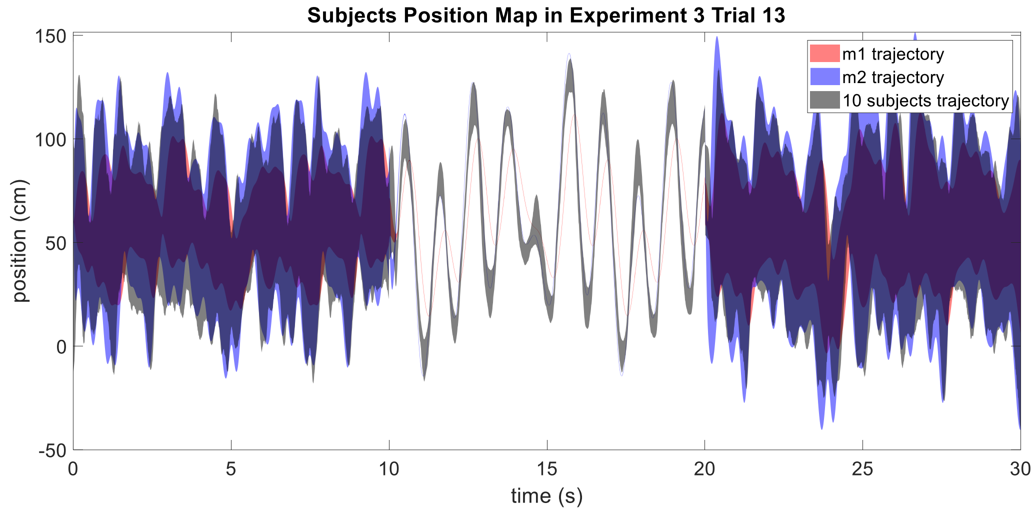

Fig. C.19. Position map of all subjects and masses for trial 13 in the experiment 3 retesting 1 day after

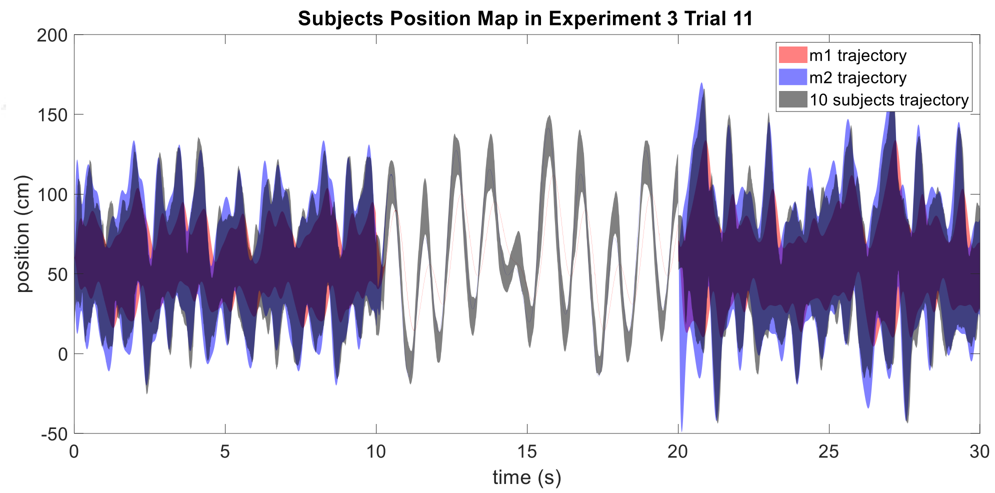

Fig. C.20. Position map of all subjects and masses for trial 11 in the experiment 3 retesting 1 week after

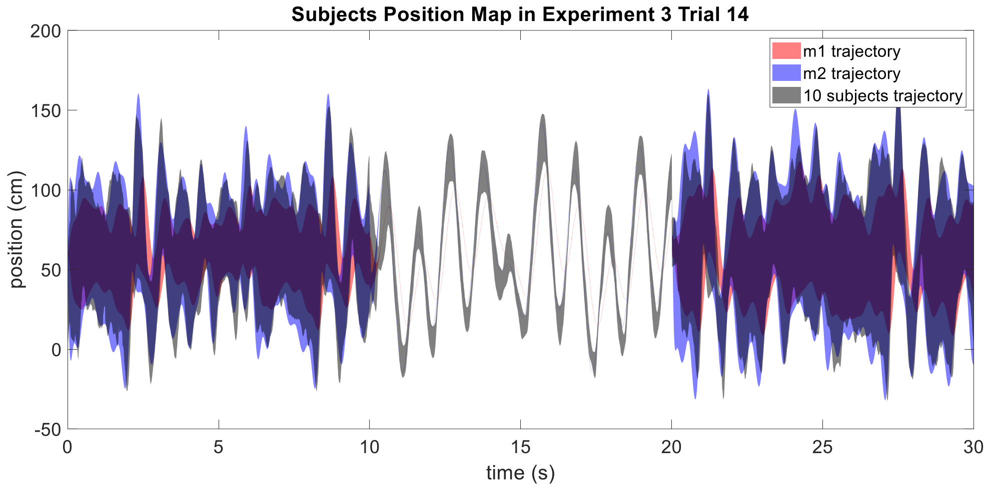

Fig. C.21. Position map of all subjects and masses for trial 14 in the experiment 3 retesting 1 week after

Table C.1 ANOVA result between segments for EMD in the experiment 3

Source	SS	df	MS	F	Prob>F
Columns	0.0011	2	0.00055	7.93	0.002
Error	0.00188	27	0.00007		
Total	0.00298	29			

Table C.2 ANOVA result between segments for RMSE in the experiment 3

Source	SS	df	MS	F	Prob>F
Columns	1.79682	2	0.89841	8.53	0.0013
Error	2.84447	27	0.10535		
Total	4.64129	29			

Table C.3 ANOVA result between segments for CV in the experiment 3

Source	SS	df	MS	F	Prob>F
Columns	0.01422	2	0.00711	8.3	0.0015
Error	0.02312	27	0.00086		
Total	0.03735	29			

Table C.4 ANOVA result between segments for SL in the experiment 3

Source	SS	df	MS	F	Prob>F
Columns	0.24811	2	0.12405	56.44	$5.37264e^{-10}$
Error	0.05495	25	0.0022		
Total	0.30306	27			

Table C.5 ANOVA result between segments for entropy in the experiment 3

Source	SS	df	MS	F	Prob>F
Columns	0.30155	2	0.15078	15.23	$4.72655e^{-5}$
Error	0.2475	25	0.0099		
Total	0.54905	27			

Table C.6 Metric analysis for 10 subjects in trial 11 and 12 to test transfer of IL in the experiment 3

Subject Number	Trial 11	Trial 12	Metric Orders	Subject Number	Trial 11	Trial 12
Subject 1	0.020	0.027	EMD	**Subject 6**	0.026	0.041
	1.079	0.868	RMSE		1.516	1.323
	0.006	0.037	SL		0.029	0.015
	0.942	0.970	CV		0.908	0.950
	3.802	3.769	SE		3.771	3.664
Subject 2	0.023	0.013	EMD	**Subject 7**	0.041	0.019
	1.012	0.818	RMSE		1.574	0.851
	0.012	0.007	SL		0.026	0.026
	0.942	0.959	CV		0.861	0.976
	3.968	3.830	SE		3.712	3.745
Subject 3	0.011	0.042	EMD	**Subject 8**	0.050	0.013
	0.754	1.754	RMSE		1.474	0.906
	0.012	0.058	SL		0.010	0.014
	0.977	0.930	CV		0.951	0.941
	3.752	3.621	SE		3.097	3.764
Subject 4	0.024	0.027	EMD	**Subject 9**	0.012	0.032
	0.970	1.128	RMSE		1.131	0.925
	0.021	0.061	SL		0.021	0.048
	0.945	0.943	CV		0.963	0.974
	3.954	3.743	SE		3.667	3.553
Subject 5	0.013	0.031	EMD	**Subject 10**	0.048	0.011
	1.495	1.073	RMSE		1.744	0.905
	0.045	0.0258	SL		0.042	0.033
	0.906	0.925	CV		0.938	0.959
	3.774	3.619	SE		3.131	3.796

Table C.7 Metric analysis for 10 subjects in trial 11 and 13 to test durability of IL after 1 day in the experiment 3

Subject Number	Trial 11	Trial 13	Metric Orders	Subject Number	Trial 11	Trial 13
Subject 1	0.020 1.079 0.006 0.942 3.802	0.013 0.966 0.012 0.935 3.766	EMD RMSE SL CV SE	**Subject 6**	0.026 1.516 0.029 0.908 3.771	0.021 1.465 0.035 0.932 3.760
Subject 2	0.023 1.012 0.012 0.942 3.968	0.021 0.880 0.056 0.922 3.812	EMD RMSE SL CV SE	**Subject 7**	0.041 1.574 0.026 0.861 3.712	0.029 1.029 0.025 0.970 3.608
Subject 3	0.011 0.754 0.012 0.977 3.752	0.012 0.778 0.028 0.969 3.824	EMD RMSE SL CV SE	**Subject 8**	0.050 1.474 0.010 0.951 3.097	0.029 1.075 0.034 0.962 3.672
Subject 4	0.024 0.970 0.021 0.945 3.954	0.020 0.783 0.010 0.955 3.752	EMD RMSE SL CV SE	**Subject 9**	0.012 1.131 0.021 0.963 3.667	0.025 1.199 0.023 0.933 3.728
Subject 5	0.013 1.495 0.045 0.906 3.774	0.019 1.480 0.049 0.932 3.812	EMD RMSE SL CV SE	**Subject 10**	0.048 1.744 0.042 0.938 3.131	0.021 0.916 0.026 0.964 3.747

Table C.8 Metric analysis for 10 subjects in trial 11 and 14 to test durability of IL after 1 week in the experiment 3

Subject Number	Trial 11	Trial 14	Metric Orders	Subject Number	Trial 11	Trial 14
Subject 1	0.020 1.079 0.006 0.942 3.802	0.027 1.035 0.027 0.953 3.711	EMD RMSE SL CV SE	**Subject 6**	0.026 1.516 0.029 0.908 3.771	0.053 1.471 0.153 0.884 3.721
Subject 2	0.023 1.012 0.012 0.942 3.968	0.078 1.616 0.096 0.921 3.445	EMD RMSE SL CV SE	**Subject 7**	0.041 1.574 0.026 0.861 3.712	0.014 1.393 0.047 0.912 3.800
Subject 3	0.011 0.754 0.012 0.977 3.752	0.027 0.994 0.020 0.981 3.708	EMD RMSE SL CV SE	**Subject 8**	0.050 1.474 0.010 0.951 3.097	0.028 1.463 0.054 0.911 3.743
Subject 4	0.024 0.970 0.021 0.945 3.954	0.028 1.074 0.032 0.985 3.714	EMD RMSE SL CV SE	**Subject 9**	0.012 1.131 0.021 0.963 3.667	0.092 1.607 0.121 0.896 3.314
Subject 5	0.013 1.495 0.045 0.906 3.774	0.060 1.240 0.080 0.939 3.671	EMD RMSE SL CV SE	**Subject 10**	0.048 1.744 0.042 0.938 3.131	0.079 1.536 0.083 0.866 3.507