Vibrotactile Perception Assessment for a Rowing Training System

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ABSTRACT

This paper presents a vibrotactile methodology for a rowing training system. Since hands' trajectories are fundamental in the rowing gesture, it is completely necessary to search and develop new technologies and techniques that can interact and help the user to perform a better movement. These methodologies must be as natural as possible in order to guarantee the transparency in the feedback of the system. Therefore this paper presents an analysis of visual, visual-tactile and tactile training strategies to understand the importance in the order and the period of time when each one is applied. Data analysis shows the importance of combining visual and tactile feedbacks to obtain the best results in the improvements of the user skills.

Index Terms: H.5.2 [User interfaces]: Training, help, and documentation; I.2.6 [Learning]: Knowledge acquisition—

1 INTRODUCTION

In the practice of rowing several motor and cognitive skills are involved, for instance the coordination between arms and legs or the execution of movement in a specific sequence. These skills have to be taken into account in the design of a successful rowing training system. At the same time the methodology and the technology behind the training system should take into account the perceptual capabilities of the human. This paper presents one aspect of the training, in particular the possibility of using vibrotactile feedback for training trajectories.

After a description of the system hardware, a rowing trajectory training is introduced. Two procedures involving visual and vibrotactile feedbacks are then shown, and the experiment design is presented. In the last part of the paper data analysis and results obtained are discussed.

2 STATE OF THE ART

Many rowing simulators are today available for rowing training. The CONCEPT2® rowing ergometer is the most employed simulator for indoor physical training and athletes performance assessment. It has been employed to evaluate injury effects on the rowing technique [12] as well as for rehabilitation [3]. Other simulators are employed both for physical and technique training. The rowing simulator developed at Sant'Anna School [5] is the platform for a rowing *training* system. No other rowing system until now has proved to be a rowing training system.

The cutaneos system receives sensory input from four different types of mechanoreceptors in the skin. Each mechanoreceptor differs depending on their properties in the skin location and response characteristics [7]. There are four types of receptor. The slow adapting receptor types (SA) displays a sustained response to a sustained stimulation, fast adapting receptor types (FA) initially respond to stimulation but stop quickly to respond if the pattern of

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stimulation does not change. The receptor of type 1 (SA1,FA1) respond to stimulation in a clearly smaller area of skin [9].
In a similar way the kinesthetic system depends on mechanoreceptors located within the muscles, tendons and joints. Different experiment has shown [4, 6] that the application of the vibration at the tendon leads to an illusion of limb movement and a change in perceived position.

We suppose an haptic feedback to be useful for rowing training as it provides mistakes awareness to the user. For instance the tactile sensation produced on the skin is sensitive to many qualities of touch. Different researches have explored the tactile sensation as a modality to present information for orientation and navigation. One example is the tactile belts that have been studied by different groups [13, 11] as promising approaches to provide directions in the horizontal plane to the user.
Lieberman and Breazeal carried out for the first time an experiment in real time with a vibrotactile feedback to compensate the movements and accelerate the human motion learning [8]. The results show how the tactile feedback induces a very significant change in performance of the user. In the same line of research Bloomfiled performed a Virtual Training via Vibrotactile Arrays [2].
Following this line of research, one approach of skill acquisition using vibrotactile feedback has been studied by Van Erp and others [14] which performed an experiment to study the instrinsic and extrinsic phenomena involved in the cognitive level when a person move his wrist through the combination of certain vibration stimuli, transmitted by 5 vibrotactile devices located in a specific part of the forearm and hand of the user. The analysis presented interesting results in the field of motion-vibration in order to know the appropriate locations and combination of vibration stimuli. It is known that vibration stimuli augment the perceptual of the user, however if this stimulus is not applied in a correct and transparent way, the user can feel a perceptional confusion.

3 ROWING TRAINING SYSTEM

The rowing training system, shown in Figure 1, is composed of a mechanical platform, a sensing system, a PC, a monitor and a vibrotactile device.

Mechanical platform   It is composed of three independent groups, a rail and two oarlocks, connected along the kinematical scheme shown in Figure 2. The platform allows the user to perfrom both sculling (rowing with two oars) and sweep rowing (rowing with only one oar), allowing also to adjust the configuration for improving user's comfort.

The oars are only allowed to rotate, their degrees of freedom, α, ϕ and γ shown in Figure 2, are the same of a real race boat oars.
For providing a realistic and functional feedback of water's resistance during the stroke this system adopted the Concept2 energy dissipating fan. The dissipating device dynamics depends only on the horizontal component of the force exerted on the handle by the user: no vertical forces are transmitted to the handle.
A transmission system composed of two bevel gears and a planetary gearbox provides the velocity multiplication needed to make the dissipating device provide the right resistance. During the recovery two freewheels disengage the dissipating device and the transmis-
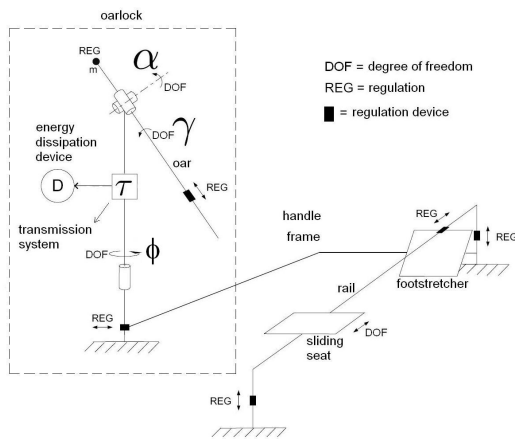
Figure 1: Rowing training system

Figure 2: System layout

sion system from the oar motion in order to avoid any resistance, as well as it happens in real rowing where the water provides resistance only during the drive phase. Additional details about the design of the system and the validation of the force profile are provided in [5].

Sensing system The oar's degrees of freedom α and ϕ are measured by means of two encoders, a third encoder measures the flywheel rotation, the oar's rotation γ is still not measured. The displacement of the seat is measured by means of two infrared sensors. Each oarlock is provided with a device for data acquisition and transmission to the PC, a third device manages and transmits data acquired from the infrared sensors. The user's head position along the rail direction is obtained by means of a webcam through computer vision analysis techniques.

PC Data acquired are stored and processed by a PC in order to analyze the performance and to provide feedbacks to the user. Performance analysis is carried out both in real time and after the performance by means of some indicators and graphs.

Monitor A LCD 40" monitor is placed before the rail in order to give the user both visual and acoustic feedback. The visual feedback usually is a virtual environment (VE) where a single scull provided with oars moves through the water with a terrestrial landscape. In the upper-left corner of the screen some performance indicators are provided.

Vibrotactile Device The vibro-tactile system used in these experiments was specially designed to control twelve vibration motors. In general terms the system consists in three PICs microcontrollers 18F4431 capable to manage 4 PWMs (Pulse Width Modulator) in hardware level with a resolution of 12-bits. The electronic design consists in a simple and conventional configuration of transistors, resistances, capacitors and diodes in order to transmit the proportional level of voltage generated by the transistors (according to the PWM signal) to the vibration-motors. One microcontroller is the master system which receives directly from the computer (via RS-232 communication) all the information related to the PWM values of each motor. The computer sends a package of 12 values which contains the vibration level of each motor. The acquisition of this information is obtained by the master microcontroller and this system transmits the information to the slave PICs via SPI interface.

4 TRAJECTORY TRAINING

A complete rowing task requires the rower to perform a complex sequence of movements wherein the body posture and the arms movements have to be coordinated. Such sequence is called *stroke* and it is commonly split in four phases [10]: the *catch*, where the rower dips the blades into the water; the *drive*, where the propelling force is exerted; the *finish*, where the blades are taken out of the water; and the *recovery*, where the rower prepares the following stroke. A skilled rower hand's trajectory retrieved on the training system and the four stroke phases are shown in Figure 3. Since the hand's
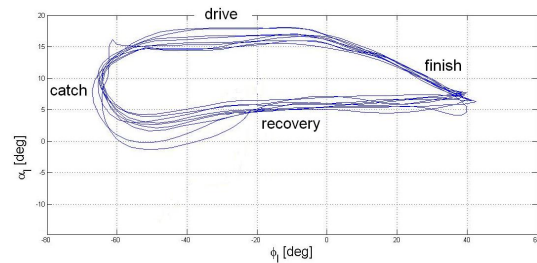

Figure 3: Hand's trajectory in the ϕ-α plane

trajectory is directly coupled with the oar motion, it turns out to be the most important factor influencing the overall performance. Therefore, it's worth for the rower to train the mastery of the hand motion. To develope the trajectory training procedure we need to define the task and the feedback provided to the user.

4.1 Task

The real oar degrees of freedom α and ϕ constraint the hand to move on a spherical surface centered on the oarlock axis. During the drive the resistance provided by the water makes the rower feel a force on the handle opposite to the hand motion, while in the other phases the motion is free. The training platform allows to reproduce indoor the same conditions, hence a procedure for the training of the whole gesture can be implemented. The system is initially calibrated: the user is guided through the correct gesture by a coach, such gesture is recorded and employed as a reference. Then the user has to reproduce such gesture without the coach guidance. Such procedure has still not been implemented: as shown in many rowing manuals [10][1], the performance of a correct trajectory involves many features which make the previously described task be associated to a lot of possible feedback. Therefore we begin with the simplest rowing-similar task which allows to separate the four stroke phases preserving the related key movements: the user has to follow a 20° by 20° square trajectory in the ϕ-α space (Figure 3), which corresponds to a little portion of the oar handle

workspace. The velocity is not constrained but the user has to follow the square in the indicated direction, motion inversions are not allowed. This simplified solution enables to assess the training system before developing the pattern gesture recording procedure, and allows to preserve some of the correct trajectory features: the lower facet represents the beginning of the recovery; the following vertical one is the entry, the hand lift is here reproduced; the upper horizontal facet represents the end of the catch, where the user still feels the opposing force; in the last vertical one the blade emersion is reproduced.

4.2 Feedback

Visual Reference A rower manages her/his hand trajectory by means of visual references and haptic feedback, keeping within the bounds due to her physical skills. For instance, during the catch the visual reference is employed to assess the boat direction, the water feedback indicates when to stop the hands lift and the shoulder litheness limits the arms spread. The chosen training trajectory is not coupled with such references and feedback, therefore we decided to provide a visual reference to make the user aware of her/his hand position.

The LCD monitor has been employed to represent four balls, the vertexes of the square trajectory, in a dark landscape. A fifth ball moves with the hand showing the hand trajectory. No feedback is provided due to a trajectory error or a motion inversion, the visual representation is only a reference.

Haptic feedback The resistance provided by the water during the drive is reproduced by the mechanical platform. The vibrotactile device provides a feedback proportional to the error when this is perpendicular to the pattern square facet ($e_\perp$), while it is constant at its maximum value when the facet limits are exceeded ($e_\parallel$) or a motion inversion is performed (Figure 4). The proportional feedback reach its maximum value when the error exceeds $1.5°$. the feedback is perceivable when the error goes over $1°$. The constant feedback due to a bound overcrossing is triggered when the error exceeds $1°$. The four motors are mounted on the two sides of the wrist (upper
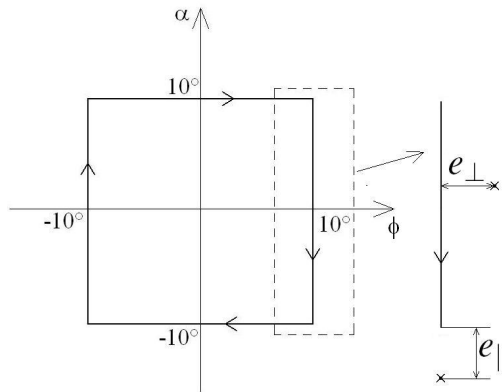

Figure 4: Training trajectory and errors definition

and lower), on the middle finger and on the elbow (Figure 5). This configuration allows to separate stimuli provided by different motors, in order to keep the transparency of the feedback. A motor is switched on once the user makes a mistake in the correspondent direction: the wrist motors switch on respectively when the hand is higher/lower than the desired trajectory, elbow motor indicates the hand is too close to the body while the middle finger one vibrates when the hand is too distant from the body. The same holds for the motion inversion. For instance let us consider the highlined box shown in Figure 4, where the hand has to move only downward. If the hand moves backward (ϕ increases) the elbow motor

is switched on, and the vibration intensity is proportional to $e_\perp$; a forward motion triggers the middle finger motor and the feedback is still proportional to the error; if the hand is taken-down too much a constant feedback is provided by the lower wrist motor until the hand reaches the correct height.
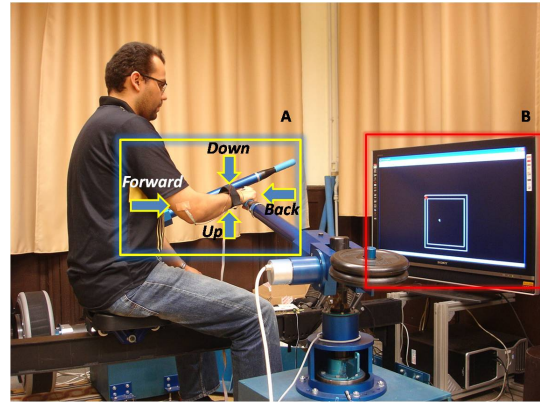

Figure 5: A: vibromotor layout and B: visual reference during a system calibration

5 EXPERIMENT DESIGN

Two training procedures have been conceived in order to evaluate the effectiveness of the vibrotactile feedback, each procedure has been carried out by a group of people.

5.1 Participants

Six participant, five males and one female, aged 25 to 35 have been divided in two groups. They are all right handed, one of them was a medium level rower and all of them have at least once experienced haptic devices.

5.2 Method

The procedure is composed of a preliminary assessment session (A_p) and three training sessions (T) each one followed by an assessment session (A). During a training session the user is provided either with the visual reference (T_v), or the vibrotactile feedback (T_t), or both of them (T_{vt}). The training sessions are spaced out each other by an assessment session (A). Each T session lasts $120\,s$ in order to make the user adapt to the session conditions and to take advantage of the feedback and the reference provided. T sessions are immediately followed by a $40\,s$ A session, while $30\,s$ of rest time spaces out an A from the following T in order to avoid fatigue. The two procedures are shown in Tab. 1.

T_v and T_{vt} sessions are employed to evaluate what the vibrotactile

	Procedure						
Group 1	A_p	T_v	A	T_{vt}	A_f	T_t	A_t
Group 2	A_p	T_{vt}	A	T_v	A_f	T_t	A_t
Time [s]	40	120	40	120	40	120	40

Table 1: Training procedures

feedback adds to the visual reference by means of an intermediate assessments A between training sessions. Therefore, since during the third T session the user is not provided with the visual reference, we decide the third A session to be the final one (A_f). The A_p and the A_f allow to take into account only the performance improvements, not depending on the previous users skills. In each A session only the visual reference is provided. The two procedures

differs for the order of T_v and T_{vt} sessions in order to exclude the learning side effect from the analysis.

Since the visual reference will be removed when the complete task will be implemented, a third training session T_t and a fourth assessment session A_t has been introduced in order to get a raw evaluation of a pure vibrotactile feedback effects.

5.3 Experiment

The participant sits on a chair between the oarlock and the rail, she/he is equipped with the vibrotactile device mounted on her/his right arm. This position does not require the user to have special physical skills in order to reach every point of the training trajectory. The experiment is divided in a preliminary phase where the participant get used to the visual reference and the haptic feedback, and a second phase where the procedure is carried out and data are stored for the analysis:

Preliminary phase The participant is asked to place the hand in the initial position $(-10°, 0)$ in the (ϕ, α) plane and to follow an horizontal trajectory for $30\,\mathrm{s}$. The visual reference (Fig. 6) is enhanced respect to the four balls case: a rectangular box representing the allowed trajectory and a red ball reproducing in real time the hand position are shown on the screen. Hence the user is aware of the bounds of the allowed trajectory, while during the following phase she/he will not. Velocity is not constrained, but motion inversion are not allowed between the ends of the facet, a vibration shows the participant when to reverse the motion. Than the same is carried out asking the user to follow a vertical trajectory, this time the initial position is $(0, -10°)$.
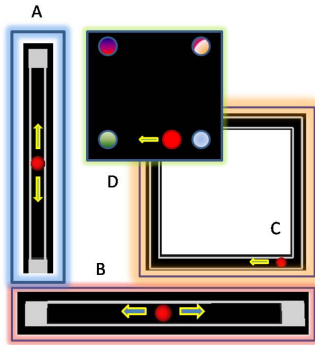

Figure 6: Visual references A and B in the preliminary phase, C in a system caliration, and D during the training procedures

Data recording phase Each participant performes A and T session depending on the group she/he is assigned to. Each session begins in the initial position $(-10°, -10°)$ where a reference ball is placed in the virtual environment. We care each A session is performed immediately after a T session have finished.

6 DATA ANALYSIS AND RESULTS

6.1 Data analysis

Each A session is compared with the pattern square trajectory. An equivalent error Δ for the performance evaluation is assigned to each session depending on the measured error, the performance is worse as the Δ is higher. Two strategies have been carried out to associate a point of the recorded trajectory to the correspondent point of the pattern, and therefore to calculate Δ:

Distance Evaluation (DE) The distance of each recorded point from the four facets of the trajectory is calculated. The minimum value is considered to be the trajectory error. The arithmetic mean of the obtained errors is the score Δ. This simple method does not guarantee that data around a trajectory corner are correctly matched with the pattern.

Data Segmentation (DS) A segmentation of the session data is initially carried out in order to separate each cycle from the others. Beginning from the initial position, data are clustered in four groups, when a geometric boundary is crossed a flag is triggered (Figure 7), after four flags have been triggered, a new turning on of the first flag closes the cycle. Error is then calculated for every facet of each cycle: data are than clustered into eight groups (Figure 7) associated to the four facets and the four vertexes of the pattern. For each point the error is calculated as the point distance from the facet whether the point is associated to a facet (e.g. B in Figure 7), while the distances from the two facets are recorded whether the point is associated to a corner (e.g. A in Figure 7). Four error arrays are so obtained, each one referred to a facet, the points associated to a corner contribute to two facets errors. The RMS method is then applied to each array obtaining the mean error committed along the facet, the arithmetic mean of such four errors is the score Δ.

The DS method results to be more accurate, moreover it allows to focus on the errors committed around an angle and to distinguish the error associated to a single facet of the trajectory. Therefore Δ and all the errors are calculated by means of this method.
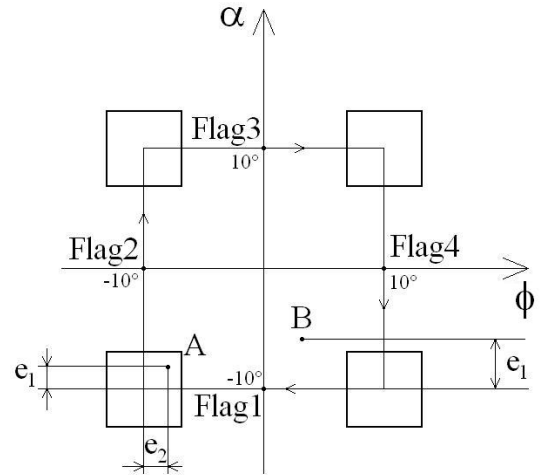

Figure 7: Data segmentation

6.2 Results

6.2.1 Procedures Evaluation

Scores Δ of the two groups of users are shown in Figure 8. The error Δ does not exceed $2.5°$, and it exceeds $1°$ only five times over eighteen (two after the A_p session). Altough such little errors, all user show an improvement between A_p and A_f. Group 1 users, who received a T_v followed by a T_{vt}, show a performance improvement after the initial T_v session, except for user two, whose performances (widely the worst among all) may be due to lapses in concentration. The continuous improvement through the A sessions may be interpreted both as a consequence of the benefits of the combined visual-tactile feedback and as an undesired consequence of a learning side effect. Group two performances analysis
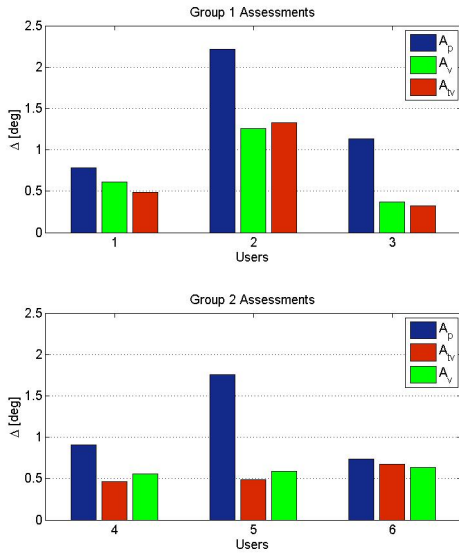
Figure 8: Sessions scores. The two plots shows the results of the assessment of the two groups in the various sessions. In the upper plot the user received a visual training followed by a visual-vibtrotactile training with a general trend of reduced error respect the visual training. The lower plot shows the effect of the visual-vibrotactile training followed by the visual one, highlighting a regression.

allows to chose one interpretation. Two of the group 2 users, who received visual-tactile in the first training session, show the best performance after the T_{vt} session. For these ones the visual-tactile feedback produces a performance improvement which is not compensated by the learning effect during the following sessions. User six represents an exception, in this case we suppose the learning effect to have compensated the benefits gap between T_v and T_{vt} sessions. Since four users over six show the best performance after the T_{vt} session, not depending on when it is carried out, we conclude the visual-vibrotactile to be an useful feedback for improving a rowing task performance.
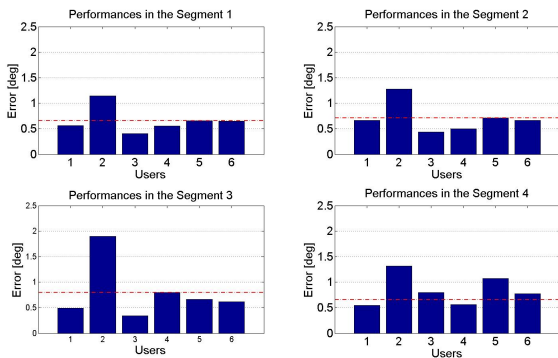

Figure 9: Segments performance. This plot shows the difference in error depending on the side of the testing square shape.

Acquired data allows to evaluate the performance within every facet (segment) of the trajectory, in particular Figure 9 presents each user error for each segment within the A sessions. These errors are calculated as the arithmetic mean of the RMS errors permormed in the same segment during different sessions.

Users error distribution through the segments is quite uniform, therefore the mean error (the arithmetic mean of the users errors) is about the same for each segment. However, we find the maximum mean error in the third segment, where the user copes with the resistance provided by the energy dissipating device.

6.2.2 Pure tactile feedback effects

It is interesting to observe the effects of the additional vibrotactile-only training comparing Figure 10 with Figure 8 for all the users. Two users over six improved their performance respect previous assessments, hence the T_t produces less benefits than a T_{vt}. Despite
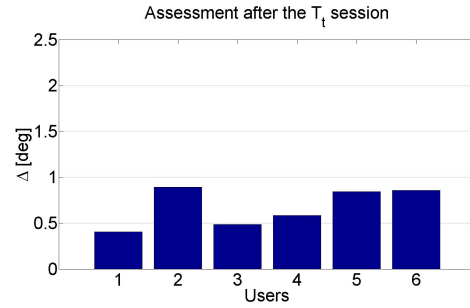

Figure 10: Assessment after the execution of the additional T_t session. All the users are presented here, with their relative scoring.

such a result, it is interesting noticing the evolution of the error inside every session. In Figure 11 the user performs a correctly shaped trajectory with more than $6°$ of maximum error. After a good start, as the session goes on, the performance worsens both as shape and as maximum error, but in the final phase of such session (black line) the user have a relevant improvement of the performance. The final trajectory is the best of the session regarding both the shape and the maximum error.
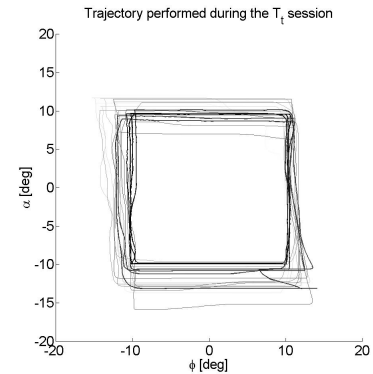

Figure 11: T_t training session results for a single user, showing the variation along time of the trajectory: the line gets thicker and darkens as the session goes on

The performance regression and the T_t evolution suggest that users are initially confused by the missing visual reference , but, as the session goes on, they get used to the feedback and they use such feedback as a new reference. When the feedback is then removed, we see a performance regression. It is worth noticing that this situation is avoided when the complete trajectory is implemented: as described in § 4.1, during a complete rowing task many references are available for the user, therefore the dependence of the user on the tactile feedback should not manifest.

6.2.3 Comments about velocity

In this paper we have have not taken into consideration velocity, it is however interesting to analyze whether velocity varies among sessions and how it is correlated with the performance. The number of cycles per sessions is an indicator of the velocity the user has kept during the session. In particular Figure 12 shows the RMS error of each user depending on the cycle. All users (except user number Two) show an increased velocity during the T_t session, while T_v and T_{vt} sessions are performed at the same velocity. Since the visual reference allows the user to guess the forthcoming error, it induces the user to be more accurate with the side effect of carrying out the task in slower way. On the other side tactile feedback does not provide the user with a future error estimation, therefore users are immediately induced to correct mistakes. It turns out that without the visual stimuli velocity increases and, at the end of the session, a better or at least equal performance respect to other conditions is obtained.
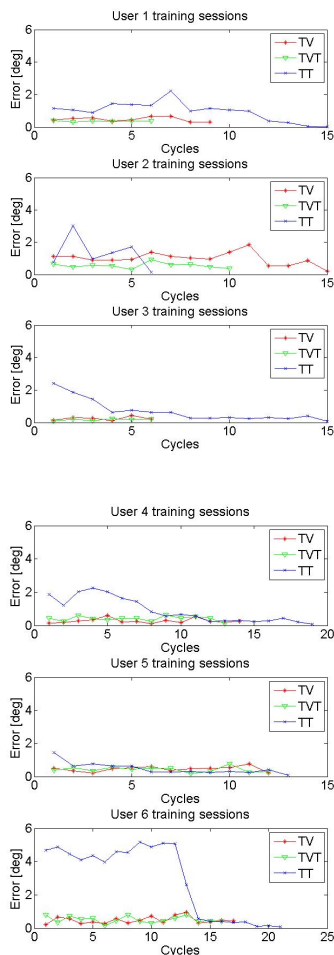

Figure 12: Error through each cycle of every T session

7 CONCLUSIONS AND FUTURE WORK

In this paper visual, vibrotactile and combined feedback have been implemented into two training procedures. Despite the reduced number of participants some conclusions can be drawn. The vibrotactile feedback improves the performance during the training phase when it is provided together with the visual feedback as shown by the benefit of T_{vt} over T_v and over T_t, independently on the order of execution. In addition to the improvement in quality of the gesture, the users show a faster execution when the vibrotactile feedback is present probably because the visual stimuli produces a slower response for correcting the errors.

This experiment will be improved first by comparing the vibrotactile against visual hints like arrows or other indicators while keeping a common reference visual stimuli. After the evaluation of this simple trajectory the full stroke will be tested, giving feedback to the user respect its energetically optimal trajectory. Finally this type of feedback will be tested in the training of other sub-skills of rowing, in particular the coordination between arms.

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