Kinematic Characteristics of Motion in the Mirror Game

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***Abstract*—We present the analysis of data collected in the mirror game setting. In our set-up two players are asked to mirror each other movements (with or without a designated leader). First, we study kinematic characteristics of motion of individual players, and next we investigate how they are affected by interactions between the players. Results of the presented analysis will be used to inform the design of interactive virtual players with kinematics based on the similarity principle.**

I. Introduction

Recently, a paradigm for studying joint motor interactions between human subjects has been proposed (see [1], [2] and references therein). This paradigm is based on the mirror game and features two human players imitating each others movements. The mirror game reflects rudimentary practices in several activities such as improvisation theatre, martial arts, or dance and music performances, which involve teams of players [3].

It is well established in social psychology that people favour interactions with others who are similar to themselves morphologically and behaviourally [4]–[6]. Furthermore, during social interaction people's movements tend to coordinate with their partners, which could be seen as a measure for interpersonal affinity [7]. Movement coordination is particularly relevant in motor rehabilitation where, for instance, patients are required to replicate movements shown to them by a clinician [8].

If the mirror game is to be played by a virtual player, or avatar, and a human being (typically the patient) then it would be necessary to manipulate the movement characteristics and features of the robot or virtual avatar playing the game. This would allow for controlling the level of movement coordination and therefore reinforcement of social bonding [9].

The scope of the European project "AlterEgo" (http://www.euromov.eu/alterego/) is to produce new robotic-based clinical methods able to enhance social interaction of patients suffering from social disabilities. Within the scope of this project a task was constructed to allow two human subjects to play the mirror game together. The main motivation for these experiments is to determine the dynamics of the players' movement in order to inform the development of the cognitive architecture which will be used in future AlterEgo experiments. A critical milestone in developing the cognitive architecture is to design a virtual player capable of tracking or leading the human patient while exhibiting kinematic properties similar to those observed in human beings. Therefore an important question is "what are the kinematic properties of motion of the human end-effector (human hand)?"

In this paper we present the statistical analysis of the kinematic characteristics of individual players' motion in the mirror game. We focus on position and velocity of the human end effector (hand). Our analysis reveals basic properties of individual player's movement that need to be taken into account when modelling the motion of the virtual player. It demonstrates the presence of coordination between players on the level of positions. It also shows the necessity of introducing an internal coordinate system for players (subjective left-right direction) for the velocity. Finally, we investigate if kinematic characteristics of mirror game movements could be used to define individual's motor signature.

The results presented in this paper will be an important first step to guide the design of virtual players that move like humans. The ultimate goal of our research is to use e mirror game as a paradigm to develop novel rehabilitation strategies for patients with social impairments. For this reason, in this paper we analyse the characteristics of movement of both healthy individuals and patients suffering from schizofrenia.

II. Experimental Set up

Participants sat opposite each other separated by a distance of 1400mm. Each sat on a 3 legged stool 450mm in height which was placed centrally on an AMTI force plate in such a way that the participants were able to comfortably rest their feet on the plate. Two horizontal strings (length 1800mm) were mounted perpendicularly at eye level centrally between the participants (separated by a distance of 150mm). A ball (diameter 30mm) was mounted on each string with a small handle (35mm) below it. Participants were instructed to move these balls left and right along the strings during the trial. The movements of each participant were collected at a sampling rate of 100 Hz using 19 reflecting markers placed on their body and on the ball itself, captured by eight infrared MX13 cameras (Vicon-Nexus, Oxford Metrics Ltd.). Five healthy pairs of participants were tested as well as three schizophrenic patients paired with healthy confederates. All participants were right handed.

III. Experimental Conditions

Four different experimental test were recorded. Each participant performed each condition 3 times for a period of 1

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minute; we refer to a single 1 minute recording as a trial. The order of the conditions was randomised. The conditions are listed below together with the instructions given to participants:

- Solo Condition (**S**). "Individual round: Play the game on your own and create interesting motions and enjoy playing." Participants had no view of their partner.
- Duo Condition (**D**). "Individual round: Play the game on your own and create interesting motions and enjoy playing." Participants had a view of their partner.
- Leader-Follower Condition (**LF**). "This is a collaborative round whose purpose is to enjoy creating synchronized motion. Participant 1, lead the movement. Participant 2 try to follow your partner's movement." Two versions of this game were played to allow both participants to take a turn at leading and following.
- Joint Improvisation Condition (**JI**). "In this collaborative round there is no leader and no follower. Let these 2 roles emerge naturally, imitate each other and create synchronized and interesting motions. Enjoy playing together."

IV. Methods

To quantify differences between players we compute the earth mover's distance (EMD) between estimated probability density functions of players' position or velocity [10]. Mathematically the EMD is special case of a Wasserstein metric and is a successful and popular tool in image analysis and pattern recognition applications [11]. In our analysis we take advantage of the fact that for two univariate probability distribution functions $p_1(z)$ and $p_2(z)$ over set Z, EMD can be computed as the L^1 distance between their cumulative distribution functions $CDF_{p1}(z)$,$CDF_{p2}(z)$:

$$EMD(p_1, p_2) = \int_Z |CDF_{p1}(z) - CDF_{p2}(z)| dz, \qquad (1)$$

where integration is over a whole set Z [11]. In practice, to find experimental CDFs we use histograms with 200 equidistant bins over maximal range of all position recordings, or over 98% of maximal range for velocity data. 2% of the data is excluded as it contains extreme values generated by numerical differentiation.

To illustrate differences between the probability density functions (PDFs), we plot covariance ellipses in the plane of mean position and standard deviation of position or the plane of kurtosis and standard deviation of velocity. (For a definition of kurtosis see [12].) To compute the ellipses we first compute unbiased estimators of four moments of the preprocessed position and velocity data. In other words, for visualisation purposes we parametrise each time series and its derivative by their means, standard deviations and kurtoses. Next, we compute mean values and covariance matrix of the suitable moments that correspond to recordings from a single player in a particular condition; 3 trials give 3 pairs of moments. Mean values of the moments give coordinates of the centre of the ellipse and eigenvectors of the covariance matrix give major and minor axes of the ellipse. Finally, the lengths of the axes of a covariance ellipse that encloses the desired probability mass are given by square roots of eigenvalues of the covariance matrix multiplied by the Mahalanobis radius [12]. Throughout the paper we use radius that encloses half of the probability mass; for that value all the computed moments lie inside the ellipse.

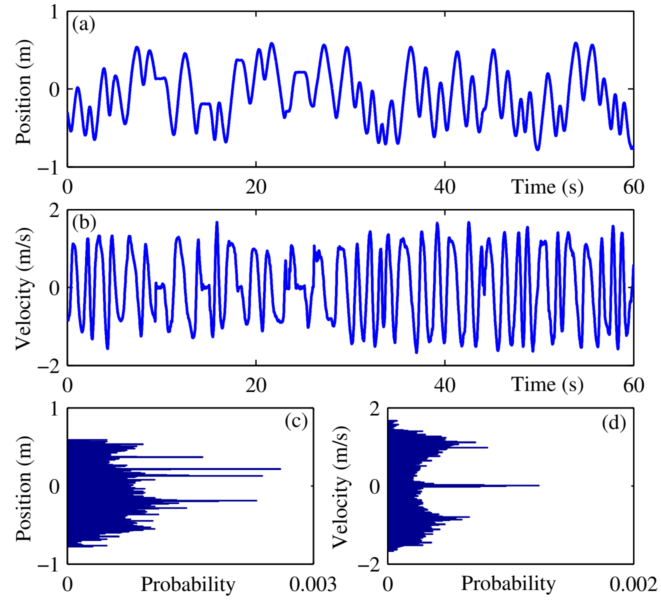

Fig. 1. (a) Time series of position $[m]$ data from a mirror game. (b) Time series of velocity $[m/s]$ computed with finite-difference method from position data. (c) Estimated probability density function of the position data from (a). (d) Estimated probability density function of the velocity data from (b).

V. Data Analysis

In order to identify kinematic characteristics of movements of human end effector in the mirror game we analyse the position data from 13 healthy individuals and 3 schizophrenic patients collected during the experiments described above. We first filter the position data with an 8th order Butterworth filter which is a maximally flat magnitude filter. Using the time series for the position of the end effector (representative example from a healthy Player 1 in (**JI**) condition is shown in Fig. 1(a)) we estimated numerically the corresponding velocity (Fig. 1(b)). To differentiate position data we use forth-order finite difference scheme (at the ends of the signal we use forward and backward coefficients).

Based on the time series of the position and velocity we compute the empirical PDFs, shown in Fig. 1 panels (c) and (d) respectively. To this end, we normalize the bins of the histogram by the area underneath which we compute with trapezoidal numerical integration. To compute empirical cumulative distribution (CDFs), we take the cumulative sum of bins normalized by the number of data points. We are using CDFs to compute the earth mover's distance between PDFs.

It is interesting to note that the velocity PDF (Fig. 1(d)) is tri-modal reflecting the alternating end effector movement to the left and to the right as the players change direction of motion that is natural during the mirror game, as well as times without movement. We observed this property of the velocity

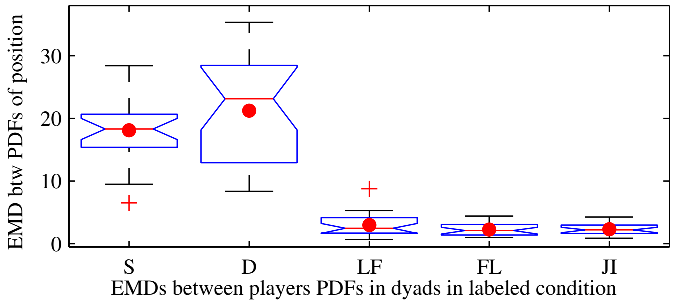

Fig. 2. Box plot of the earth mover's distances between position PDFs of players performing together (in a dyad) in different conditions. S – distances between position PDFs of players in solo condition; D – distances between position PDFs of players in duo conditions; LF and FL – distances between position PDFs of leading and following players; JI – distances between position PDFs of players in joint improvisation condition. Red line shows median; red dot shows mean; top and bottom of blue rectangle are first and third quartiles; whiskers – lowest and highest datum within 1.5 of interquartile range. Red cross show data outside whiskers.

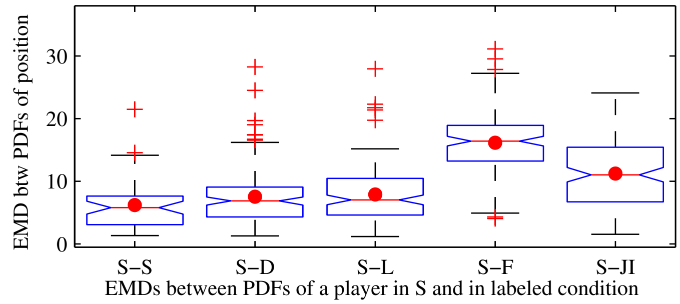

Fig. 3. Box plot of the earth mover's distances between PDF of positions of a player in solo and in the other conditions. S-S – distances between position PDFs solo trials of a player; S-D – distances between position PDFs of solo and duo trials of a player; S-L – distances between position PDFs of solo and leader trials of a player; S-F – distances between position PDFs of solo and follower trials of a player; S-JI – distances between position PDFs of solo and joint improvisation trials of a player. Markings are the same as in Fig. 2.

PDFs consistently in our data in the case of both, healthy individuals and patients.

VI. Coordination in dyads

Having estimated the PDFs for each individual in each of the four conditions in which the mirror game was played we proceed by computing the earth mover's distances (EMDs) between PDFs of players positions (see Methods section). We are using EMD, rather then statistical tests for comparing distributions, because we are interested in quantifying differences between players.

We start by quantifying the behaviour of players performing together in different conditions. Fig. 2 shows the distribution of distances between position PDFs of players performing together in the same dyad and in the same condition. Each box plot in Fig. 2 illustrates the distribution of distances for all dyads performing a given condition. We find that in solo (**S**), and duo (**D**) conditions distances between PDFs are much bigger than in the conditions in which players were instructed to interact, leader-follower (**LF** or **FL**) and joint improvisation (**JI**).

The box plots in Fig. 3 show distributions of distances between PDFs of an individual player in different conditions. For example, the S-S column shows distribution of the distances between the three solo trials of individual players; the distances are computed separately for each player and next plotted together as a box plot. In particular, the position PDFs of a player in the duo condition or leading in leader-follower condition are closer to his/her PDF in a solo condition than when the player is following or performing a joint improvisation condition. The PDFs differ most from the solo condition when the player is following in the leader-follow condition, S-F column. The distances between solo trials and joint improvisation trials of the given player (column S-JI), for all players are on average shorter than the distances from the solo to the follower condition and longer than the distances from the solo to the duo condition. This observation demonstrates that individuals who are acting as "followers" tend to tune their movements to the "preferred kinematics" of the leader.

In the case of the position PDFs, the EMDs can be visualised on the plane of the two first moment of the PDFs, namely the mean and standard deviation of players' position. To illustrate the differences between the position PDFs for every player we take the first two moments of three trials in a given condition, and instead of plotting them as three points (number of non-repeating combinations between different elements of a three element set) we visualise them as a covariance ellipse in the (mean, standard deviation)-plane (Fig. 4).

Panels (a) and (c)-(f) in (Fig. 4) depict healthy players' dyads in all four conditions; panels (b), (g) and (h) of Fig. 4 depict dyads in which one of the players was a patient; players 4, 13 and 15 respectively.

We can clearly see that the ellipses that correspond to (**S**) and (**D**) conditions are markedly different from the ellipses for (**LF**) and (**JI**). This observation nicely demonstrates the interaction between players that takes place when they are leading and following each other or jointly improvising. Moreover in (**LF**) condition the ellipse of the player that is following moves towards the preferred region of the player that is leading and vice versa (Fig. 4). In contrast, when playing in the (**JI**) condition, in most of the cases, the ellipses of the players move to an intermediate range of motion, in other words they 'meet' in-between the preferred movement ranges of each of the individual players (Fig. 4). Differences in the mean positions of players movements are consistent with the performed condition and with the fact that all players were right-handed and were sitting in front of each other. In particular, if zero position represents the centre of the body, then the natural movement of the right hand will have an offset due to the fact that its axis of rotation (shoulder) is placed to the right from the spine; the observed values of the offset agree with the human anatomy.

A natural way to avoid interaction in the duo condition is for the players to move away from each other to the opposite parts of the string. We observe that in the mean position of ellipses –

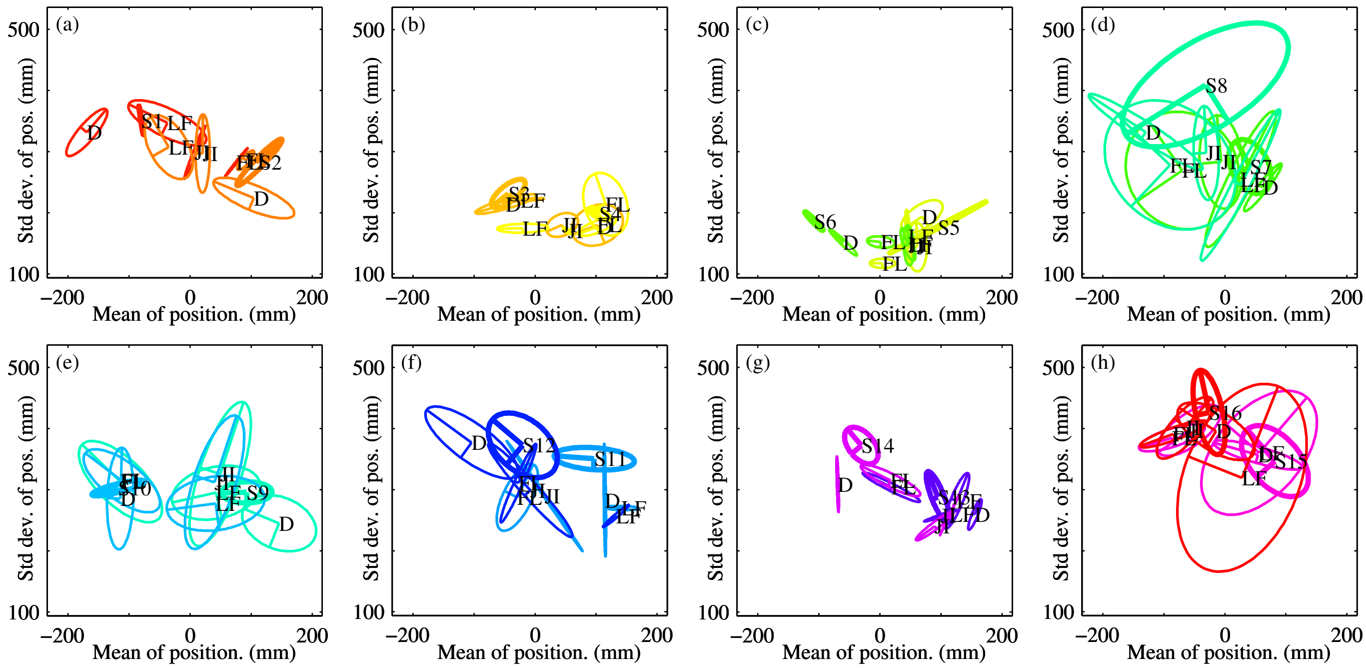

Fig. 4. Illustration of interactions between players in the mirror game. Regions in the mean and standard deviation of position [mm] PDF plane corresponding to different players and conditions are indicated by covariance ellipse for a bivariate Gaussian distribution of means and standard deviations of position PDF (half of the probability mass of the Gaussian lies inside the ellipse). Players are indicated by colours, conditions are indicated by labels: Sn – solo, $n = 1, \ldots, 16$ (thick line), D – duo, LF and FL – leader/ follower, JI – joint improvisation. (a) Dyad 1, healthy players; (b) Dyad 2, player 4 is a patient; (c) Dyad 5, healthy players; (d) Dyad 7 player 13 is a patient.

labelled D in Fig. 4, and in column D in Fig. 2 - position PDFs of players performing together in duo condition are further away from each other, than position PDFs of the players belonging to the same dyad performing in solo condition; also compare with column S in Fig. 2. In most of the panels in Fig. 4 we see that ellipses labelled LF, FL and JI overlap. That means that if the players are interacting they have a common range of movement. This similarity of movement is illustrated in columns LF, FL and JI in Fig. 2 by very low values of EMDs between position PDFs of players belonging to the same dyad in the respective conditions.

Using similar inference we can analyse differences in movement of individual players performing different conditions. In columns S-D and S-L in Fig. 3 we show that the range of movement of player in the (**D**) condition and when the player is leading in the (**LF**) condition is similar to the range of movement of the same player in the (**S**) condition. On the other hand, when acting as a follower in the (**LF**) condition, the player has to move his/her arm to the left to get to the leader's range of movement, that also means that the player will be the furthest away from their solo condition and closest to the solo position of their partner. Furthermore, in the joint improvisation both players are moving towards each other, and both of them are roughly equally away from their own solo positions. These observations are depicted in the columns S-F and S-JI in Fig. 3. More generally, these observations show that distances between PDFs can be used to quantify changes in player's movement.

Additionally, Fig. 3 shows that to study differences in kinematics of individual players it is necessary to orient the data with respect to the internal coordinate system of the player. Such an internal coordinate system is given by the direction of movement towards and away from the central axis of the body; movements of the arm in these directions are controlled by different muscle groups.

VII. Two kinds of motor signature

A crucial aspect of the experimental design in the AlterEgo project [13] involves creating kinematics for the virtual player, which are either similar or different from those of the patient playing the game with the artificial agent. To address this question we proceed by analysing similarities and differences between PDFs of players' velocities. We want to know if players' velocity PDFs are consistent enough between trials to be used as an individual motor signature. In the analysis of velocity PDFs we use the internal coordinate system of the players.

In Fig. 5 we show box plots of distances between velocity PDFs from all conditions performed by a given player. Each column corresponds to a different player; players 4, 13 and 15 are patients. We find that all columns, except 13 and 15, look quite similar. For some players velocity PDFs remain very similar in consecutive trials and conditions (e.g. player 11 or 16), for others they differ more between each other (e.g. player 1 or 8). However, for patients 13 and 15 medians of distances between velocity PDFs are above 75th percentile of distances for all the other players.

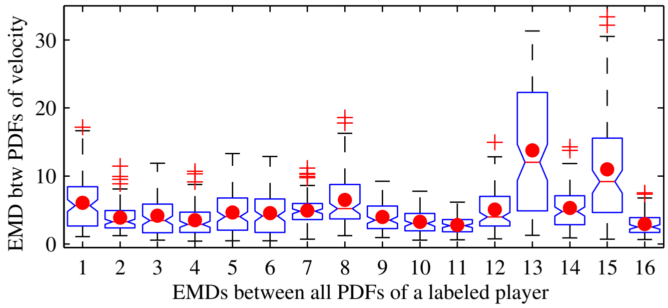

Fig. 5. Box plot of the earth mover's distances between velocity PDFs from all conditions performed by a player. Labels correspond to individual players; players 4, 13 and 15 are patients. Markings are the same as in fig. 2.

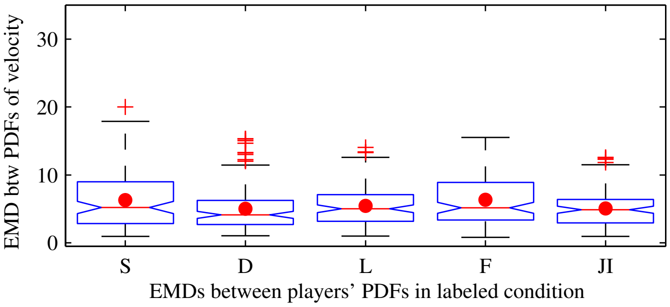

Fig. 6. Box plot of the earth mover's distances between velocity PDFs of all players performing given condition. Each column corresponds to a different condition: S – distances between PDFs of players in solo condition; D – distances between PDFs of players in duo conditions; L and F – distances between PDFs of leading and following players; JI – distances between PDFs of players in joint improvisation condition. Markings are the same as in Fig. 2.

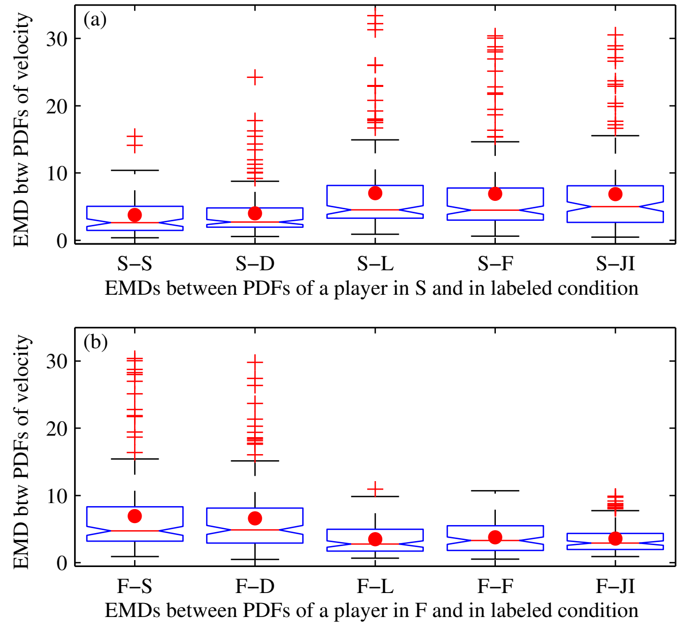

Fig. 7. Box plot of the earth mover's distances between PDFs of velocity of a player in solo and in the other conditions (a). S-S – distances between PDFs of solo trials of a player; S-D – distances between PDFs of solo and duo trials of a player; S-L – distances between PDFs of solo and leader trials of a player; S-F – distances between PDFs of solo and follower trials of a player; S-JI – distances between PDFs of solo and joint improvisation trials of a player. (b) Following in leader-follower condition and in the other conditions; labels as above F stands for following in leader-follower condition. Markings are the same as in Fig. 2.

In Fig. 6 we depict distances between velocity PDFs of all players performing in a given condition. Each column corresponds to a different condition. Fig. 6 shows that differences between all players in a given condition are as big as differences between velocity PDFs of a player in all conditions. However, we see that distances between velocity PDFs of players in solo condition and players that are following in the leader-follower condition have wider distributions than the distances between velocity PDFs in the other conditions. This indicates that in those two conditions players' velocity PDFs are the furthest away from each other, implying that the players movements differ most from each other.

To explore that observation further we analyse in more details distances between velocity PDFs of individual players in different conditions. In Fig. 7 (a) we show distances between PDFs of the velocity of a player in solo and in the other conditions, and in panel (b) of a player following in the leader-follower condition and in the other conditions. Each column represents distances between all player's trials in the given conditions collected from all players. Panel (a) in Fig. 7 demonstrates that distances between velocity PDFs of a player performing solo and duo conditions have the same range as distances between the PDFs from the solo condition trials and are smaller than distances between the velocity PDFs of solo condition trials and in leading, following and joint improvisation trials of a player. Panel (b) in Fig. 7 shows similar result for distances between velocity PDFs for trials when given players are following in the leader-follower condition and when they are leading in the leader-follower or when they are performing joint improvisation condition.

Next we compare Fig. 6 and Fig. 7. We observe that distances between solo trials of a player, column S–S in panel (a) of Fig. 7, and between following trials of a player, column F–F in panel (b) of Fig. 7, are smaller than distances between solo trials of different players, column S in Fig. 6, and between following trials of different players, column F in Fig. 6. This indicates that velocity PDFs of trials in solo condition are similar for individual players and at the same time different enough between players that they can be used to define solo motor signatures. We observe similar trends for the velocity PDFs of trials in which a given player is following. However, because in the leader-follower and joint improvisation conditions we find very strong coordination between players these PDFs characterize dyads, rather than individual players.

To better visualize observations from Figs. 5 and 7 we plot covariance ellipses in the plane of kurtosis and standard deviation of velocity. In panel (a) Fig. 8 we plot the ellipses for the (**S**) and (**D**) trials of all players and in panel (b) for the (**LF**) and (**JI**) trials. In panel (a) we see that trials in (**S**) and (**D**) conditions have on average lower kurtosis and higher standard deviation then the trials in the other conditions, compare with

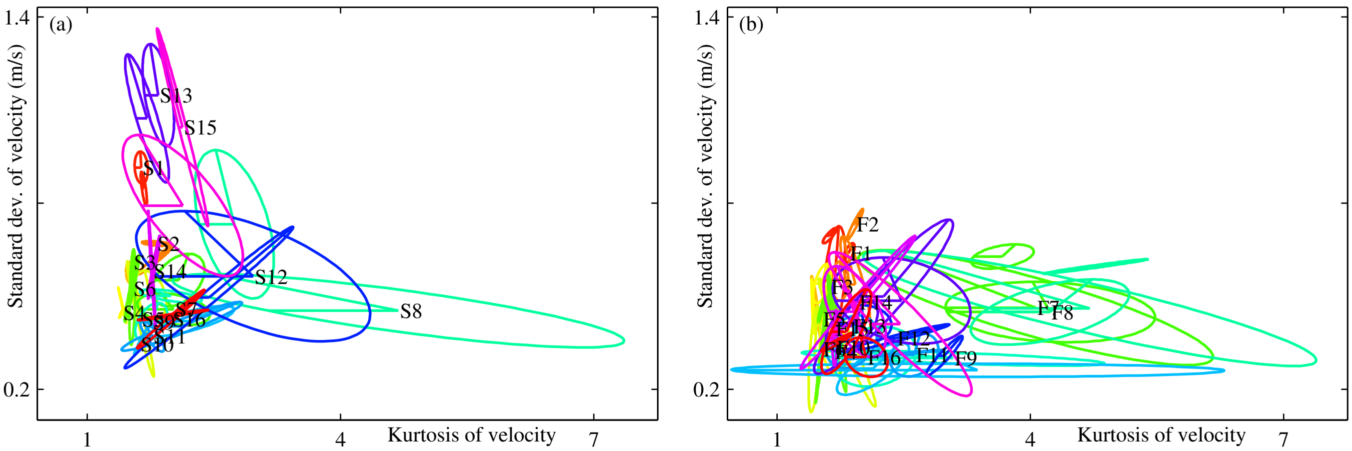

Fig. 8. Regions in the plane of kurtosis and standard deviation of velocity PDFs corresponding to different players and conditions. Covariance ellipses in panel (a) are for trials from solo and duo conditions and in panel (b) for trials from leader-follower and joint improvisation conditions. Labels and colours are the same as in Fig. 4.

panel (b). In particular, patients 13 and 15 have the highest standard deviations of the velocity PDFs for the (**S**) trials. These high values of the standard deviation explain the big ranges of distances visible in Fig. 5. Changes of locations of ellipses for individual and cooperative conditions, between panels (a) and (b) in Fig. 8 correspond to the change between panels (a) and (b) in Fig. 7.

VIII. Discussion

Having performed the analysis above involving the PDFs of position and velocity of motion of the end effector we conclude that one of the ways of measuring kinematic similarity in the context of the mirror game is by means of EMDs between the position and velocity PDFs. EMD allows to quantify kinematic similarity between players even if their movements are uncorrelated. Furthermore, it appears that differences between PDFs in solo condition can be used to differentiate between patients and healthy individuals. Finally, our analysis suggests that the PDF of the velocity of players performing (**JI**) and/or (**LF**) conditions could be interpreted as a motor signature of a dyad.

The relation between individual motor signature and behaviour of a player in cooperative conditions is a subject of ongoing investigation. To find such a relation, it would be necessary to analyse repeated mirror games of a group of players assigned to different dyads. Such an experiment can be performed using a virtual player. Analysis of human players movements while interacting with a virtual player that behaves in a different but controlled manner in every game would allow us to identify an individual motor signature that is preserved even when players are interacting with each other.

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