Human Motion in Cooperative Tasks: Moving Object Case Study

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***Abstract*—This paper describes results obtained in a preliminary investigation of a cooperative task consisting, for a pair of human operators, in moving a handle-shaped object between two predefined locations on a table. Seated, the operators use only upper body with single hand and arms in achieving this task. In a first step, each subject realized the task in a standalone mode. In a second step, pairs of subjects realized a similar task in a cooperative way. We used standalone results as a reference model to be compared with results obtained from cooperative experiments. Obtained results revealed that it is difficult to fit the minimum jerk model as a task motion characterization in both standalone and cooperative modes. However, we found an invariant velocity shape both for standalone and cooperation situations that can be used as a basic model for a robotic implementation. We noticed that the shape of the parabolic trajectory is always higher in cooperative tasks, although the weight of the object used in cooperative mode is exactly twice the one used in a standalone mode.**

I. Introduction

We are interested by knowledge and models of human haptics in physical cooperative tasks involving an object intermediary, which we term *person-object-person* (POP). Examples of such tasks include cooperative object handling and transportation, cooperative assembly, etc. Our aim is to collect or gain knowledge which will allow us to model efficient cooperative control strategies on virtual or robotic humanoids in order to perform interactive cooperative physical tasks with humans. This preliminary investigation focuses only on cooperative displacement of an object on a table, and studies only the motion used to perform this particular task.

In the following we will first review some studies of human behavior both for free space motion and for contact, with and without objects. Our concern is to know whether the motion behavior in performing this moving object task in a standalone mode extends to the same task performed in collaboration between dyads.

II. A brief review

Optimal control proved to be relevant in explaining human motion. In a synthetic review of the optimality principles governing human sensorimotor motions, two general approaches are distinguished [1]: (i) open-loop optimization that can explain average behaviors, (ii) closed-loop optimization that can explain detailed behaviors in reaction to environment change or in task learning.

Different open-loop optimization criteria seem to be used by humans in different behaviors. Metabolic energy minimization gives very close results to real human walking motion [2]. The minimum jerk model has been found to predict arm movements [3]. The minimum torque change model [4] allows predicting experimentally obtained motions, yet at the price of more complex motion calculation, etc. These minimum principles do not give any explanations why biological systems would minimize them. In [5] it is advocated that explanatory theories failed because they do not take into account all the limitations of the biological system. Such an explanatory theory has been also proposed in [6] which claim that human arm movements maximize accuracy (or minimize variance) in the presence of motor noise. Yet such a model is difficult to implement and at present is impossible to use for real-time motion planning of robot motions. In this paper, we will then restrict comparison with the minimum jerk model.

As for the interaction with the environment, Hogan [7], [8] shows that human muscle architecture allows controlling the impedance of the arm, and that impedance must be adapted to the task. There is strong evidence [9] that human indeed adapts its impedance to the task, but feedback must also be used [9]). While it is possible to know which impedance to use when the admittance of a task is known, it remains the problem of how human identifies task admittance. The problem of cooperative tasks seems to be more complex since the admittance of the task will depend on the partner's impedance: both partners could use low or high impedances.

Some work studied the bimanual manipulation [10] with the influence of weight. Engelbrecht also studied effect of a weight. There is also work in robotics based on minimum jerk model and impedance characterization of human arm, see for instance [11] [12] and more recently [13]. In the first two references, the minimum jerk model was supposed to apply in cooperative mode. As we will see in this paper, the minimum jerk model is not applicable for the task we studied, even for its realization alone. Our work follows similar objectives to that of Reed [14] where a thorough review of dyadic interactive task is provided. At this stage however, we are interested in understanding the collaborative motion independently from the haptic communication issues.

We propose to study a cooperative motion of moving an object, including leaving and reaching contacts. Our contribution is twofold: (i) the study of this motion including leaving and reaching a contact from the minimum jerk model point-of-view and the derivation of a practical motion model; and (ii) the comparison between standalone and cooperative movements.

III. Methods

We study a basic moving task of an object in the 3D Cartesian space, from a predefined spot to another. Both spots are within the range of the reachable space for each operator. Moreover, placements are chosen so that each operator's arm can achieve the task far from singular postures and without an excess of efforts.

There have been two groups of experiments. The first one, used as a reference, consists for subjects in moving the object in a standalone mode. The second group consists in performing the same task in a collaborative mode. We describe hereafter, the subjects, the precautions we took for the experimental apparatus and the procedures for collecting data.

A. Subjects

6 healthy subjects, 5 right handed and one left handed, participated in the first group of experiment. The experiments agree with the ethical rules governing our institution and all the subjects gave informed consent. From these subjects, and after evaluating the standalone results, we gathered 3 pairs of persons to undergo the collaborative task. We explain later how these pairs have been gathered.

B. Experimental setup

Subjects were seated in front of a table on which stands the sensor-instrumented object to move. Their hands and shoulders are free to move, the table height is adjusted so that the motion is as less constrained as possible.

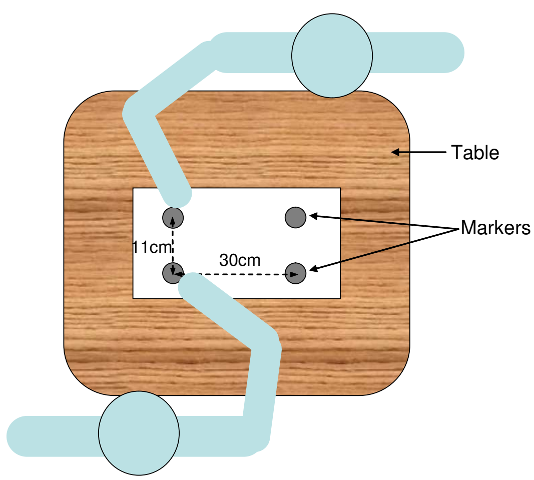

Fig. 1. Schematic view of the apparatus.

On the table, see Fig. 1, visible markers are drawn on a sheet of paper; they indicate points from and to where the object has to be moved. The points are drawn as gray colored plain circles. Circles are chosen not to induce any orientation for the reaching pose of the object on the marker. The circles are set so that their surface is entirely covered by the object when posed, so that subjects do not try to precisely position the object on the markers.

Each object is shaped as a cylindrical handle, see Fig. 2. Standalone and cooperative objects were designed to have the same shape and dynamics effects in both standalone and cooperative tasks: the weight of the object used in the standalone experiments is exactly half of the object used in the collaborative experiments. At the bottom of each handle is attached a 6 degrees of freedom (dof) force sensor and at the top two 3D position and orientation trackers. For the tracking, we used the MiniBird magnetic trackers from Ascension Technology; technical data are available on the website[1]. We added a soft material to reduce impacts. We took care to avoid as much as possible ferric materials in the experimental volume which may alter the measurement of magnetic trackers. However, we used aluminum handles, which can perturb the position measurement. But we took care to attach miniBird probes far enough from the handles. We checked the positioning accuracy using a calibration procedure which revealed a precision below 3mm for the absolute positioning.

MiniBird measurements are sampled at 145Hz. All the data are collected from a single PC placed relatively far from the experimental setup. Since we used a non-real time operating systems, we took special care for the retrieval of all measurements and their synchronization.

C. Procedure

For the standalone object moving experiments, subjects were instructed to grasp the instrumented object's handle and move it to a circle-mark shown prior to the experiments, Fig. 2. When the object is put on the destination mark, the subjects are asked to perform a very short break and bring it back to the starting circle. Subjects are instructed to perform 25 go-and-back motions. The recording starts from the very first motion to track possible learning phase.

From the standalone experiments we selected dyad for cooperation experiments. The two first pairs built from subjects having similar mean task times: Sub. M (0.93sec) with Sub. S (0.80sec), and Sub. T (1.11sec) with Sub. K - acronym 'Sub.' stands for subject and the following letter is the first letter of the subject's name. The remaining pair consists of subjects with different mean task times: the left-handed Sub. L (1.45sec) with Sub. F (1.06sec). The pairs of subjects are instructed to move the object as in the standalone mode. The subjects are seated in front of each other, but with shoulders of the arm performing the task nearly aligned with the middle of the sheet and table.

No specific behavior is dictated to the subjects. Also, the subjects were not constrained to move the object or the hand/arm through any specific path to reach the target. No specific timing constraint is imposed to realize the task. The handles/objects used in the standalone experiment are the exact copy of those used in the cooperative experiment.

Positions and orientations are recorded. Position of the middle of the handle is estimated from the position and

[1]www.ascension-tech.com/products/minibird.php

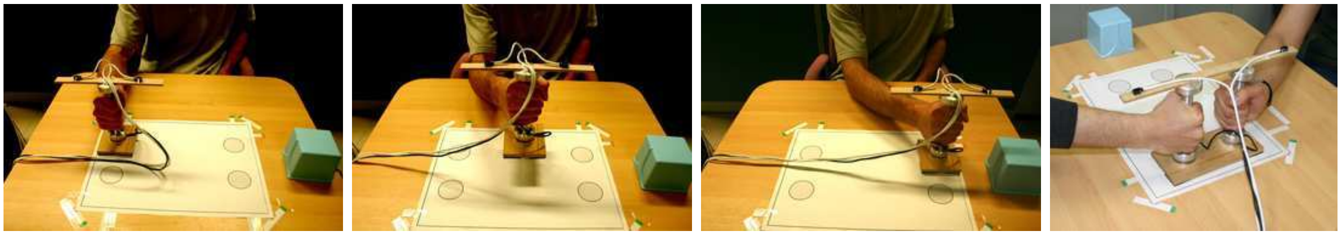

Fig. 2. Photos of the experimental apparatus during realization of moving object task in standalone situation (3 first pictures). Photo of the experimental apparatus for study of cooperative motions (last picture).

orientation of the probes. Positions are then filtered with a third order Butterworth forward and reverse filter with a 25Hz cutting frequency. Speed trajectories are obtained by numerical derivation of the position. Determination of the beginning and the end of each motion during a sequence is obtained with a proper threshold tuning on the norm of the velocity. To facilitate data processing, each motion can be supposed to take place in a plane with a good approximation. Therefore we determined the best least-square fitting plane to study each motion.

IV. Results

A. Standalone experiment

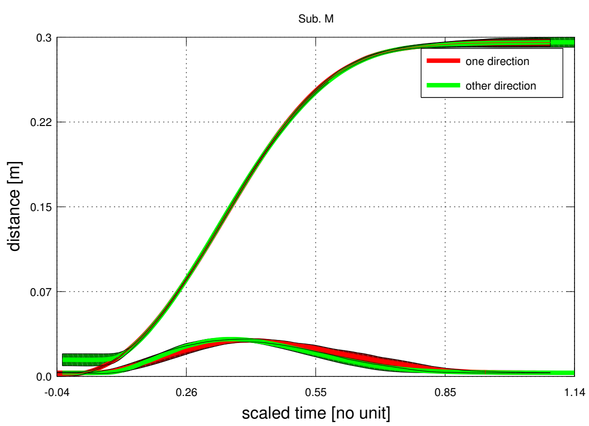

Fig. 3. Mean trajectory along x- (going from 0cm to 30cm) and z- (going from 0cm to 3.5cm) axes in function of time for standalone experiment. The mean trajectory is computed from the 20 last motions. The motions have been scaled in time and distance to maximize superposition before computing the mean. The surfaces surrounding the mean motions represent the variance of the motions around their mean motion. The green and red tick curves are the mean trajectories for opposite directions of motion.

We recorded 6 subjects realizing the task of moving the object 25 times in one direction alternated with 25 times in the other direction. Positions of the middle of the handle are represented in the best fitting plane of the motion. For all motions, the origin point has been set as the origin of the current motion coordinates. Whatever the direction of the motion, the direction of the coordinates is set so that all motion start from 0 and goes to positive x values. z-axis is chosen

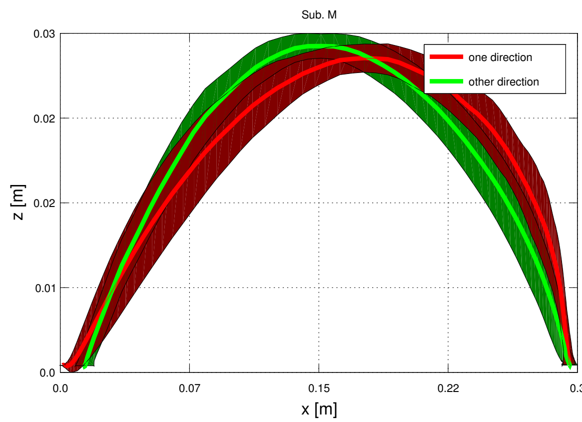

Fig. 4. Mean trajectory in the plane of motion for standalone experiment. The mean trajectory is computed from the 20 last motions. The motions have been scaled in time and distance to maximize superposition before computing the mean. The surfaces surrounding the mean motions represent the variance of the motions around their mean motion. The green and red tick curves are the mean trajectories for opposite directions of motion.

vertical. Motions represented are the mean of the 20 last trials (10 last motions in one direction and the 10 last motions in the other direction). Fig. 3 represents the x an z components of the mean motions and variance with respect to time for Sub. M. Fig. 4 represents the mean motion in the fitting plane with variance for Sub. M. Fig. 5 represents the x and z components of velocity with respect to time for all subjects with variance.

For all these data, before computing the mean value, the best scaling of signals was determined to minimize the area between curves. Both time and amplitude of motion were scaled. Due to the discreet nature of the signals, the area between them is not smooth with respect to the scaling parameters. Classical SQP methods were not efficient for this problem. We used the code SolvOpt which deals with non-smooth problems instead, see [15]. This scaling allows to see better the shape of the motion, and is valid under the assumption that motions are scale invariant, as for the minimum jerk model, see [3]. Another advantage is the reliability of the method to compare motions. Indeed we observed variations at the end of the motions that can be attributed to vision-based feedback. Our method relies on the whole motion to make the superposition and was not sensitive to those variations. On the contrary,

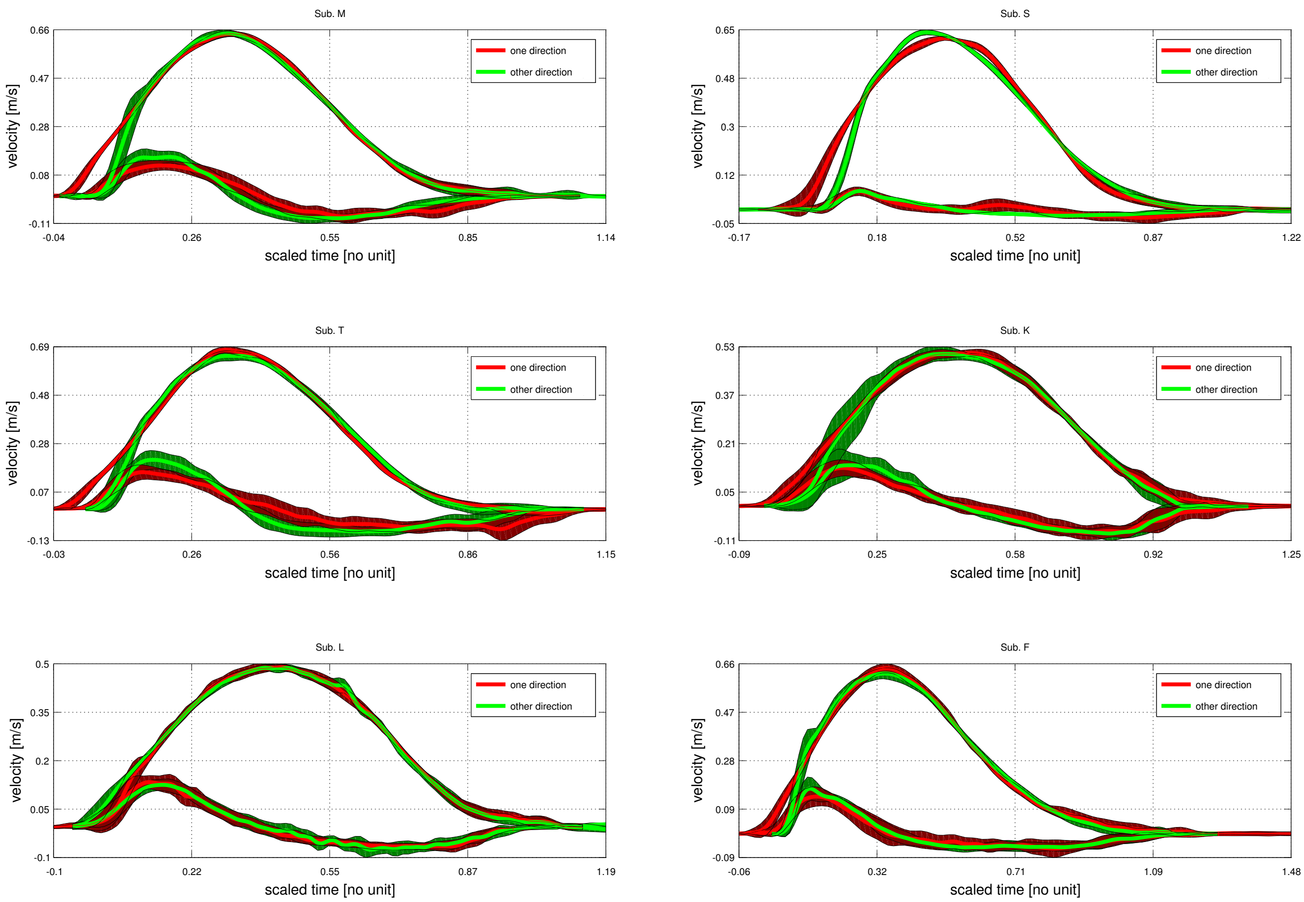

Fig. 5. Mean velocities for all subjects in the standalone experiments; the mean trajectory is computed from the 20 last motions. The motions are scaled in time and distance to maximize superposition before computing the mean. The surfaces surrounding the mean motions are the variance of the motions around their mean motion. The green and red tick curves are the mean trajectories for opposite directions of motion.

a method based on a threshold on velocity to determine the beginning and end of the motion is very sensitive to those feedback artifacts.

B. Cooperative movement

Table II presents the average maximum height of the standalone and cooperative motions. Mean velocities for the standalone task Fig. 6 and for the cooperative tasks Fig. 7 are presented for the 3 subjects pairs, using optimally scaled data.

The table I presents a comparison of mean times for the realization of the task. The duration of motion do not substantially alter the directions of motion.

V. Discussion

We will first discuss standalone motions, and we will discuss in a second step the effects of cooperation on the motion.

A. Underlying model of the task motion

We first checked some properties of the motions. Figs. 6 and 7 present the mean velocity profiles of our experiments with the time and the velocity's amplitude scaled as presented earlier. Note that all velocity profiles are very close. Those motions, as the minimum jerk, are then scale invariant, and can all be approximated by a basic motion shape.

We have studied different models that could give the motion shape obtained. The minimum jerk model [3] in its simplest form predicts straight-line motions between two points of interest. Our case study obviously does not result in a straight-

TABLE I

Times of motions. The values presented correspond to the average time over the last 10 motions in each direction. The two lines for a pair of subjects correspond to the different directions. The third column correspond to the average over subjects.

	Standalone task			Cooperation task
	Sub. 1	Sub. 2	Av.	
Sub. M. and S.	0.92	0.80	0.86	0.91
	0.94	0.79	0.87	0.88
Sub. T. and K.	1.16	1.21	1.18	1.17
	1.06	1.20	1.13	1.14
Sub. L. and F.	1.43	1.08	1.26	1.16
	1.47	1.03	1.25	1.12

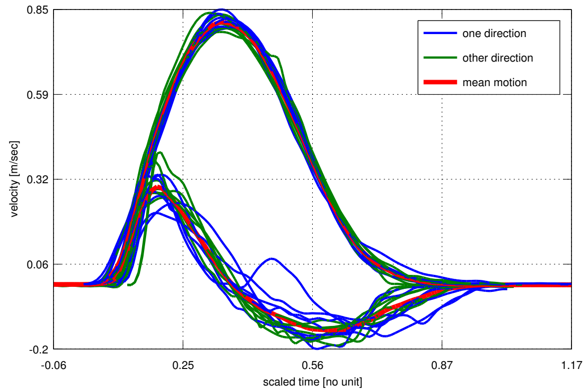

Fig. 6. Superposed averaged velocities over the last 20 motions for the standalone tasks of all subject. All mean velocities are scaled to obtain the best superposition and a good comparison. The mean of all standalone tasks is also represented. It can be noticed that all subjects have very similar velocity profiles, when scaled.

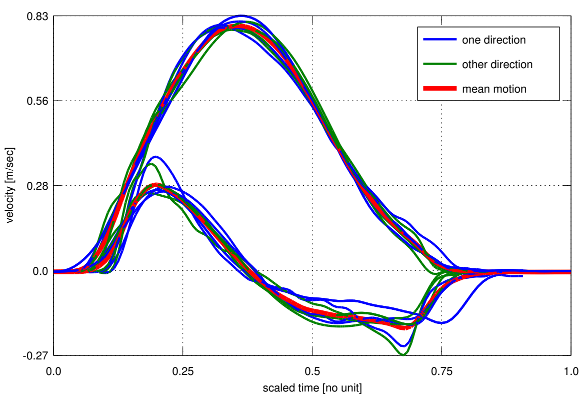

Fig. 7. Superposed averaged velocities over the last 20 motions for the cooperative tasks of all pairs. All mean velocities are scaled to obtain the best superposition and a good comparison. The mean of all standalone tasks is also represented. It can be noticed that all pairs have very similar velocity profiles, when scaled.

line motion, as can be seen on Fig. 4. To consider minimum jerk fitting with a curved path, it requires setting via-points. We tried to fit such a model with one via-point, the time at which the intermediate point is reached being a result of the optimality criterion, as presented in [3]. We solved numerically the minimization of the area between the minimum jerk curve and the measured curve with the initial, intermediate and final time as parameters as well as the intermediate point position. However we did not obtained a good fit, as can be seen on Fig. 8. We also obtained a bad fit for the minimum jerk with normal constraint for grasp reaching [16]. Therefore those models do not allow explaining or predicting such velocity asymmetry. The shape of velocity profiles for x-axis have

TABLE II

MAXIMUM HEIGHT OF MOTIONS (IN CM). THE VALUES PRESENTED CORRESPOND TO THE AVERAGE HEIGHT OVER THE LAST 10 MOTIONS IN EACH DIRECTION. THE TWO LINES FOR A PAIR OF SUBJECTS CORRESPOND TO THE DIFFERENT DIRECTIONS. THE THIRD COLUMN CORRESPOND TO THE AVERAGE OVER SUBJECTS.

	Standalone task			Cooperation task
	Sub. 1	Sub. 2	Av.	
Sub. M. and S.	3.3	1.2	2.2	6.3
	2.5	2.8	2.7	4.9
Sub. T. and K.	3.6	4.0	3.8	7.0
	3.4	4.1	3.7	6.1
Sub. L. and F.	3.5	2.4	2.9	4.3
	3.4	3.4	3.4	4.0

already been reported in the literature [17], [18]. We obtained a good match of the motions using two fifth degree polynomials (as for minimum jerk) but letting free the intermediate position, velocity and acceleration, as can be seen on Fig. 8. This model is simpler than [19]. However it is not based on a basic neuro-muscular principle. For the time being, we did not find any neuro-muscular principle explaining the motions we obtain and this is left for future work. Nevertheless, it is possible to parameterize such a motion and predict the velocity profile for various speeds and motions amplitude. However, the vertical motion seems more dependent to each subject, as can be seen from Figs. 6 and 7. This might be due to the fact that there is no precise task associated with the vertical movement; there is just the table that must be avoided in the vertical direction while moving the object.

We can see on Fig. 5 some patterns based on the direction of the motion: for all the subjects but left-handed Sub. L the second direction starts with higher acceleration than the first direction. For the left-handed subject the same pattern appears in the other direction, which proves an arm configuration dependency of the motion shape.

B. Characteristics of the cooperation

In the previous section, we observed that human motion for moving an object does not follow any existing model, but it is scale invariant and can be represented by two judiciously chosen polynomials. We will now compare the cooperative motions with the standalone motions and pinpoint the characteristics of the cooperative behavior, whether similar or different to the standalone behavior.

The first interesting behavior we notice on table II which compare standalone and cooperative maximum height, is that all subjects tend to perform a motion which is much higher in cooperation task relatively to the standalone one. We do not have yet a clear explanation of this phenomenon, but it is significant, e.g. especially for the two first subjects pairs. It cannot come from the difference of weights since we took care to have a standalone object having exactly half the weight of the cooperative object. It could be linked to the perception of the force that can be underestimated, see [20]. As explained, each operator may predict and compensate the force

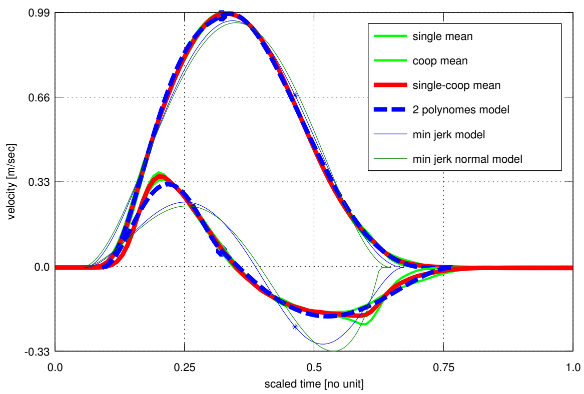

Fig. 8. Velocities of averaged single and cooperation motions, their mean, and the fit of different models. The fit is performed on the positions and observed here on the velocities. Note that single and cooperation motions are very similar. Model of two 5th degree polynomials is fitting perfectly the horizontal velocity and quite well the vertical velocity. Minimum jerk model with intermediate point and minimum jerk model with tangential contact reaching are not able to represent precisely the motions.

due to own motion, but maybe without taking into account the partner contribution, hence an overthrown motion. Future investigations would be necessary to have a more thorough explanation.

From velocity profiles Fig. 7, note that, after scaling, all the motions in cooperation superpose well, even if durations of motions –as seen in table I– are different. Furthermore from Fig. 8, we can see that shapes of standalone motions is very similar to shapes of cooperation motions. Therefore the shape of the motion seems to be an invariant characteristic for the realization of the task, for the single as well as for the cooperation case. This shape of motion could then be used as a model for a proactive cooperation application, as in [21], to improve the quality of the collaboration.

For the times of motions in Table I, notice that the motion times in cooperation are in between those of the individual subjects respectively. The cooperative task time is close to the mean value of the standalone task time for the same subjects, and strictly between the minimum and maximum values of the same subjects.

VI. Conclusion

In this paper we investigated a basic human cooperative task consisting in moving a handle-shaped object between two predefined locations on a table. Obtained results revealed that the minimum jerk model fitting is not good to characterize this task. However we noticed a particular shape of motion in the horizontal plane that is scale invariant. This shape can be identified and used as a primitive to predict more accurately a motion than the minimum jerk model. Also, we noticed that the shape of the parabolic trajectory is always higher in cooperative tasks. Finally we found that motions durations in cooperation are close to the mean of motions duration for the same task realized individually. This study opens doors to more investigations that we will undergo as future research. Namely: find the underlying principle explaining the observed velocity profile, study of interaction forces, and an implementation on human-robot interaction.

Acknowledgment

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