33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Classification of strategies for disturbance attenuation in human-human collaborative tasks

A. Melendez-Calderon*, *Graduate Student Member, IEEE*, V. Komisar*, G. Ganesh, *Member, IEEE* and E. Burdet, *Member, IEEE*.

Abstract— **Rigorous analyses of the mechanisms human-human physical interaction are only possible if corresponding means of systematically classifying dyad strategies are in place. Previous suggestions for classification of strategies neglect the high level of redundancy that is present when attenuation of external disturbances is required. To address this, we propose a quantitative classification system based on combined interaction force and EMG recordings of the flexion and extension activities of each partner in a given dyad.**

I. INTRODUCTION

In the context of motor skill acquisition, physical contact is recognized as a valuable means of helping others gain motor skills and accomplish tasks, as seen in common rehabilitation interactions between therapists and patients. Despite a plethora of anecdotal evidence that supports the value of tactile and haptic interactions in motor skill acquisition, very few studies have been conducted to explore the mechanisms of these interactions in depth.

The work in [1] was pioneering in identifying certain individual specializations that are seen when two humans collaborate to accomplish a task. Its results suggest that human-human haptic interactions are advantageous in accomplishing certain tasks typically done by individuals (e.g., moving a cursor to a target as quickly as possible) and disadvantageous in others (e.g., disturbance rejection). However, it did not account for redundant muscle strategies. The study [2] proposed alternative specializations, where "execution" and "conductorship" were defined as the main roles in a haptic interaction task. [3] investigates the consistency of dominance behavior in trials with haptic/visual and visual-only feedback between partners undertaking a collaborative task and shows that differentiation between individual roles is more pronounced when the haptic component is present.

We are particularly interested in understanding how the central nervous systems of the dyad deal with noise and instability [4]. Attenuation of such perturbations typically occurs from mechanical impedance due to muscle properties and reflexes [5]. While an individual controls the endpoint impedance through coordinated muscle activations [6], in an interaction task performed by two subjects (dyad) it can be controlled using various strategies between the partners, including co-contraction by one partner, pulling or pushing together, etc. A dyad system therefore has, in addition to the kinematic redundancy, a large muscle redundancy, both of which need to be examined. Given these redundancies, which cannot be distinguished solely through kinematic and interaction force data, what are the strategies and degree of specializations that a dyad can adopt to accomplish a collaborative task under external disturbances?

We surmised that the additional information about activity at the muscular level would bring more clarity to the mechanisms of physical collaboration between the partners in a given dyad. We accordingly propose an automatic quantitative classification system based on combined interaction force and EMG recordings of the flexion and extension activities of each partner in a given dyad. Here we present our system, which will serve as a necessary tool for subsequent evaluations of dyad strategies in collaborative tasks.

II. STRATEGIES FOR DISTURBANCE ATTENUATION IN HUMAN-HUMAN COLLABORATIVE TASKS

Subjects took part in a set of dyad experiments conducted on the Hi5 interface (Fig. 1; [7]). These experiments consisted of tracking a periodically moving target in cooperation, i.e., the subjects were mechanically coupled and tracked the same target. Each subject was presented with the same visual feedback, which consisted of a moving target (represented by a solid polygon of 4^o width) and their (common) wrist angular position (represented by a blue line) (Fig. 1). The target was programmed to move periodically at $0.2Hz$ on a $[-20^o, 20^o]$ range using minimum jerk moving patterns. Subjects were asked to track the target during 30 intervals of $20s$ duration. External $3Hz$ sinusoidal torque perturbations of different amplitudes were applied to the subjects' wrists by the Hi5 interface. Perturbations started at $0Nm$ torque (no perturbation) for the first 10 trials; then increased to $0.5Nm$ for the subsequent block of 10 trials; and finally to $1Nm$ for the final 10 trials in the experiment. Subjects were given a $20s$ rest period after each trial. In our descriptions, the partners standing in the left and right positions will hereafter be described as *green subject (G)* and *yellow subject (Y)* respectively.

Manuscript received March 29, 2011. This work was supported in part by EU grant FP7-ICT-271724 HUMOUR.

*These authors contributed equally to this work

A.M, V.K. and E.B. are with the Department of Bioengineering, Imperial College of Science Technology and Medicine, United Kingdom (e-mail: {amelende, eburdet}@imperial.ac.uk).

G.G is with the Computational Neuroscience Lab, ATR, Kyoto, Japan

978-1-4244-4122-8/11/$26.00 ©2011 IEEE

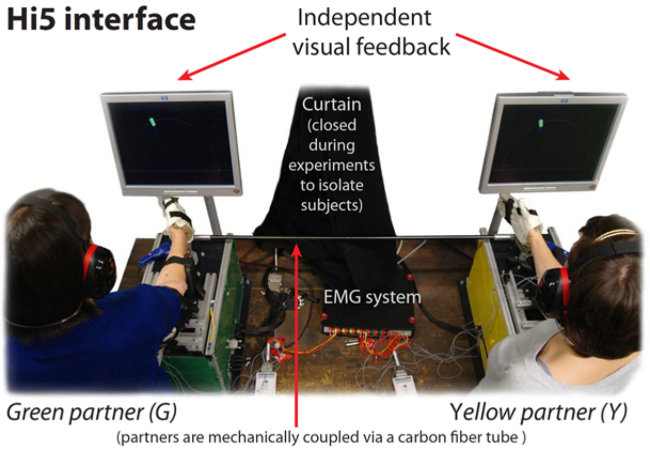


Fig. 1. Overview of the Hi5 system. The figure shows the partners of a dyad performing a collaborative tracking task by holding handles, mechanically coupled via a carbon fiber tube. Surface EMG, interaction torques and kinematic data is recorded from both participants. Subjects are separated by about one meter (and a curtain) and wear hearing protection to avoid non-haptic interactions.

Surface electromyography (sEMG) from both flexor-carpi radialis (FCR) and extensor-carpi radialis longus (ECR) were normalized with respect to levels observed during a calibration process *(i)* relaxation, *ii)* maximum voluntary (MV) flexion, *iii)* MV extension and *iv)* MV co-contraction), prior to the trials.

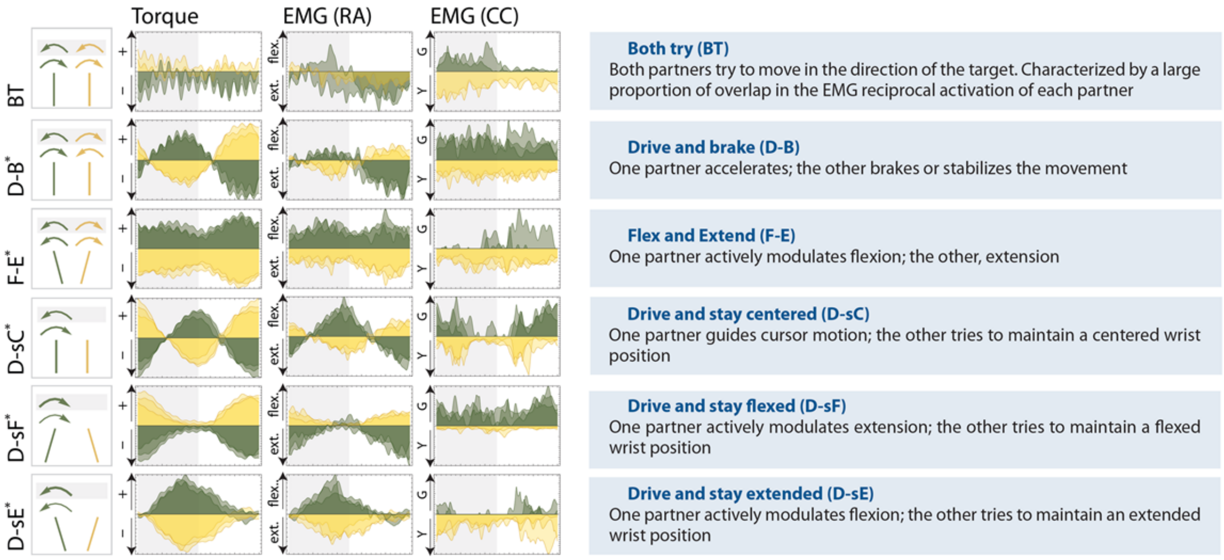
In our descriptions, EMG reciprocal activation (RA) is defined as $\mathrm{EMG}_{\mathrm{Flexors}}$–$\mathrm{EMG}_{\mathrm{Extensors,}}$ while co-contraction (CC) is defined as min($\mathrm{EMG}_{\mathrm{Flexors}}$,$\mathrm{EMG}_{\mathrm{Extensors,}}$).

A. Definitions of strategies

In preliminary experiments performed with twelve naïve subjects, we noticed that dyads adopted different strategies to guide cursor motion, attenuate disturbances and ultimately keep the cursor in the target. Some of these dyads switched strategies between trials for reasons that are not immediately apparent. We also noticed that there was a high degree of overlap in the reciprocal activation between dyad partners in the initial trials. This suggests that partners initially attempted to assume the same roles in guiding cursor motion and keeping it aligned with the target. As the trials and level progressed, this overlap decreased, indicating that each partner assumed a greater degree of specialization.

Based on these observations, we deduced that it was necessary to develop metrics that would allow us to systematically identify and classify strategies based on interaction force and EMG data, and make subsequent inferences about the processes that take place when a given dyad adopts or abandons a particular strategy.

We observed similarities in some of the approaches adopted by dyads. We conjectured that these approaches could be classified into five *base strategies* (*i) Drive and Brake (D-B), ii) Flex and Extend (F-E), iii) Drive and stay center (D-sC), iv) Drive and stay flexed (D-sF), v) Drive and stay extended (D-sE)*; Fig. 2). These strategies depict means by which individuals in a particular dyad can contribute to overall motion and successful task completion as a pair in terms in terms of interaction torque patterns. Furthermore, we can define an additional strategy that represents when both partners try to move in the direction of the moving target and are competing for the driving role. If classification is based solely on the analysis of interaction torques, the system might suggest the dyads are interacting with a certain strategy but the intention of the partners would differ from the result measured at the mechanical level. We call this strategy *Both try (BT)*, and we propose to quantify the probability of this strategy in terms of the percentage of the attempt on which the dyad reciprocal EMG activations



Both try (BT)
Both partners try to move in the direction of the target. Characterized by a large proportion of overlap in the EMG reciprocal activation of each partner

Drive and brake (D-B)
One partner accelerates; the other brakes or stabilizes the movement

Flex and Extend (F-E)
One partner actively modulates flexion; the other, extension

Drive and stay centered (D-sC)
One partner guides cursor motion; the other tries to maintain a centered wrist position

Drive and stay flexed (D-sF)
One partner actively modulates extension; the other tries to maintain a flexed wrist position

Drive and stay extended (D-sE)
One partner actively modulates flexion; the other tries to maintain an extended wrist position

*These examples are defined in terms of the *Green* partner adopting the "drive" role (for D-B, D-sC, D-sF and D-sE) or "flex" role (for F-E). These roles could similarly be adopted by the *Yellow* partner, giving rise to an additional five "reciprocal" base strategies

Fig. 2. Characteristic patterns of the different strategies observed in dyads during a periodic tracking task. External perturbations are set at 0.5Nm. Green and yellow represent the partner on the left and right respectively. Note that for clarity of the plots, co-contraction patterns for the yellow participant are displayed on the negative axis.

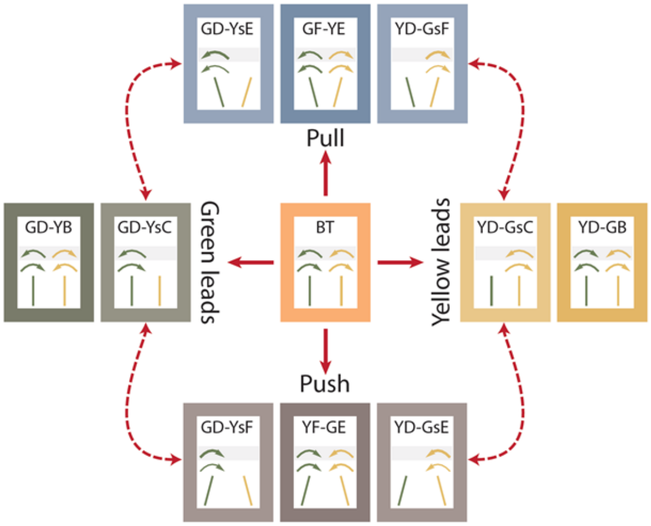


Fig. 3. Organization of the different identified strategies. Strategies are arranged such that transitions between strategies that are close together are more likely to happen.

.

overlap. Note that the individual roles on each of these *base strategies* can be reversed (e.g., instead of green driving and yellow braking, yellow could drive and green could brake), giving rise to five more possible strategies taken by the dyad. All observed strategies are presented in Fig. 3.

It is important to note that these representations only describe in broad terms the strategy that a given dyad adopts. Within each strategy, partners in a dyad can also modulate the overall impedance by varying their individual co-contraction level. For example, as external perturbations of increasing magnitudes are applied, the overall impedance of the dyad can be varied by either partner applying a high level of co-contraction relative to the other, or both partners applying comparable levels. An example of this redundancy is illustrated in Fig. 4, in which the dyad interaction torque patterns are similar, but the amount of co-contraction provided by each of partners is different. To properly describe a strategy adopted by a dyad, the contribution in terms of co-contraction levels of each partner should be included - adding specificity to a description of a dyad's strategy.

B. *Characterization of strategies*

A simple way to estimate the most probable strategy taken by a dyad during a particular attempt is to define a set of *strategy templates* on which interaction torque data is compared. We propose a method on which torque measurements are normalized and compared against these templates and a probability value is assigned to each of these strategies. Based on the information from EMG, one could also include the probability of both partners performing the BT strategy, as well as add specificity to these strategies by indicating the co-contraction levels provided by each partner to attenuate the disturbance.

We performed a second round of experiments with another ten naïve right-handed subjects to test our classification system. Fig. 5(a,c,e) shows the evolution of the most probable strategies taken by three dyads throughout the course of the experiment (specificity levels in terms of co-contraction are not provided in this figure), while Fig. 5(b,d,f) shows the distribution of calculated probabilities across a whole perturbation level for each of the dyads.

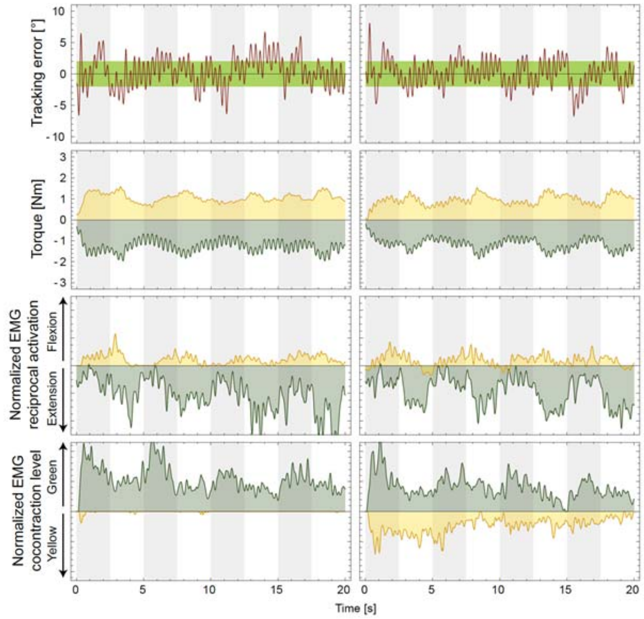


Fig. 4. An example of redundancy: the dyad perform on the same perturbation level (0.5*Nm*), with similar strategy on both trails (as suggested by the interaction torque patterns), but with different co-contraction levels to attenuate the external disturbance (left – only green contributes with high co-contraction; right – both partners contribute)

Both partners in Dyad 1 (Fig. 5a,b) alternated roles frequently as the trials progressed, suggesting that their behavior was unstable. Conversely, Dyads 2-3 (Fig. 5c,d and Fig. 5e,f) evolved from strategies in which one partner uses alternating activation of flexors/extensors for driving the movement and the other damps the movement (either actively or passively), to strategies in which a form of pushing or pulling against each other is required. These strategies were seen frequently at the higher perturbation levels, which necessitate high impedance for maintaining cursor stability. Note that the transitions between strategies for these two dyads occurred as depicted in Fig. 3.

We noted that subjects often adopted the BT strategy in the first period of motion in each trial, which aligns with both partners attempting to guide the cursor in the direction of the moving target. Transitions to different strategies often occurred shortly after that, as subjects diverged into more specialized roles.

III. DISCUSSION

We have developed a quantitative classification system that can be used to automatically identify which strategy partners in a dyad are applying to undertake a collaborative tracking task. This will facilitate future quantitative analyses of these dyad strategies and help us better understand why a

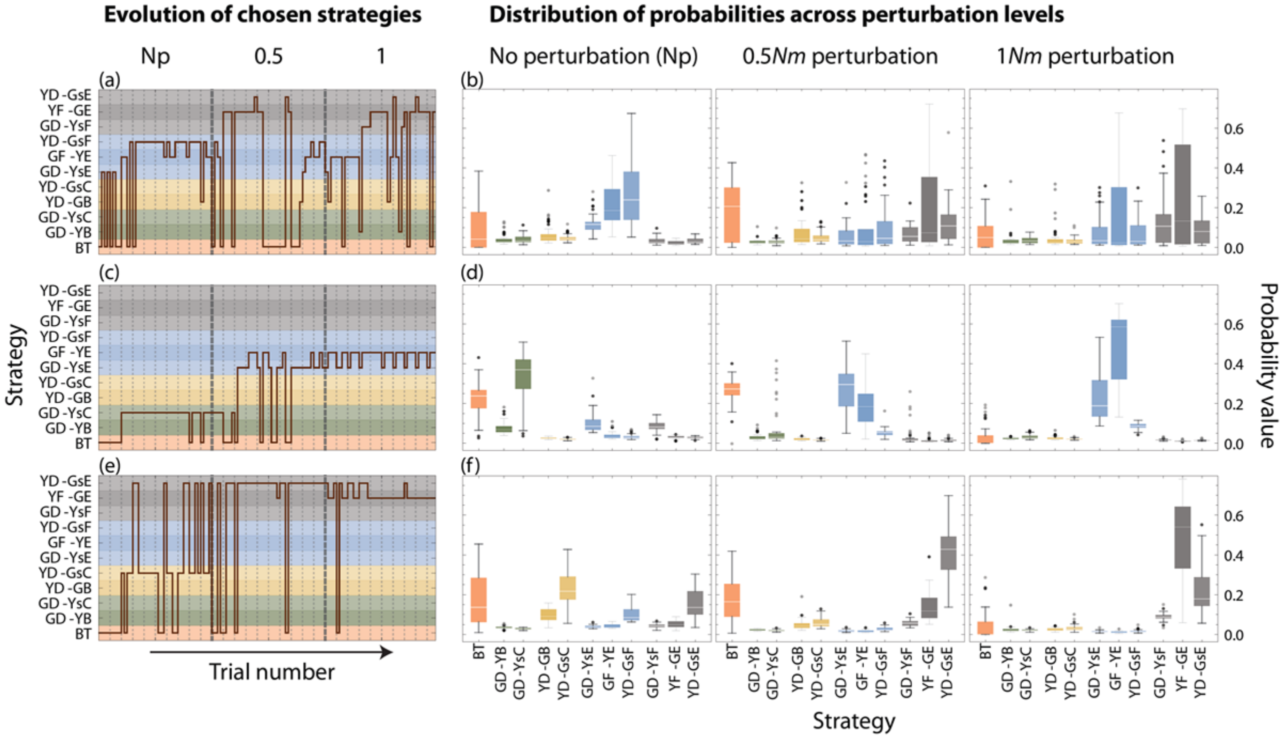


Fig. 5. (a,c,e) Evolution of most probable strategies taken by three dyads during a periodic tracking task with different levels of external noise perturbation. Thin-dotted vertical lines indicate the start of a new trial, while thick-dashed vertical lines indicate a change in the perturbation level. (b,d,f) Whisker plots of the probabilities for each strategy across a whole perturbation level (for the same three dyads). Each box shows the distance between two quartiles surrounding the median, and boundary lines indicate the range of the data set without outliers. Outliers are defined as those points beyond 1.5 times the interquartile range from the edge of the box and are represented as a dot.

dyad might favor one particular strategy over another at a given time and if there are any trends in evolution of strategies in instances where dyads approach the tracking task in different ways over the duration of the experiment.

We noticed that some of the tested dyads did not apply the same strategy across trials. A better understanding of this evolution and the factors that cause it (e.g., fatigue, discrepancies in the capabilities of the partners) would add to our knowledge of how human-human haptic interactions progress with respect to time. Our quantitative classification system for dyad collaboration strategies will be helpful in testing hypotheses on how changes in dyad strategy occur.

It is also important to consider the individual capabilities of the partners in a given dyad. These can be defined through a number of metrics, including tracking accuracy, trajectory smoothness and capacity to attenuate perturbations. Our future work will involve ranking subjects based on their individual trials and analyzing how individual capabilities may have affected strategy selection and role specialization. It will be especially important to contrast dyads in which there is a large discrepancy in capabilities (e.g., one partner is much stronger than the other) with dyads in which the partners are more similar, as this could greatly impact the approach that the partners take.

Finally, it will be crucial to analyze dyad data in the context of strategy and relate it to such metrics as interaction force stability, energy expenditure, and trajectory smoothness. This could provide us with insights as to whether certain strategies are advantageous for these purposes, which could also be useful in optimizing robot behavior for certain human-robot collaborative tasks.

REFERENCES

[1] K. B. Reed and M. A. Peshkin, "Physical Collaboration of Human-Human and Human-Robot Teams," *IEEE Transactions on Haptics,* vol. 1, pp. 108-120, 2008.

[2] N. Stefanov, A. Peer, and M. Buss, "Role determination in human-human interaction," in *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, 2009, pp. 51-56.

[3] R. Groten, D. Feth, H. Goshy, A. Peer, D. A. Kenny, and M. Buss, "Experimental analysis of dominance in haptic collaboration," Toyama, 2009, pp. 723-729.

[4] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance," *Nature,* vol. 414, pp. 446-449, 2001.

[5] G. Ganesh, A. Melendez-Calderon, M. Haruno, M. Kawato, and E. Burdet, "Transitions between reciprocal activation and co-contraction in wrist posture control (*submitted*)," *Journal of Neurophysiology,* 2011.

[6] D. W. Franklin, R. Osu, E. Burdet, M. Kawato, and T. E. Milner, "Adaptation to Stable and Unstable Dynamics Achieved by Combined Impedance Control and Inverse Dynamics Model," *Journal of Neurophysiology,* vol. 90, pp. 3270-3282, 2003.

[7] A. Melendez-Calderon, L. Bagutti, B. Pedrono, and E. Burdet, "Hi5: a versatile dual-wrist device to study human-human interaction and bimanual control (*submitted*)," in *IEEE/RSJ international conference on Intelligent robots and systems*, San Francisco, USA, 2011.