

Robotic light touch assists balance

# 1                    **Robotic light touch assists human balance control**

## 2                    **during maximum forward reaching**

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26                    Word count: 4447

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47 **Abstract (<250 words)**

48 **Objective**

49 We investigated how light interpersonal touch (IPT) provided by a robotic system supports human individuals  
50 performing a challenging balance task compared to IPT provided by a human partner.

51 **Background**

52 IPT augments the control of body balance in contact receivers without a provision of mechanical body weight  
53 support. The nature of the processes governing the social haptic interaction, whether they are predominantly  
54 reactive or predictive, is uncertain.

55 **Method**

56 Ten healthy adult individuals performed maximum forward reaching (MFR) without visual feedback while  
57 standing upright. We evaluated their control of reaching behaviour and of body balance during IPT provided by  
58 either another human individual or by a robotic system in two alternative control modes (reactive vs predictive).

59 **Results**

60 Changes in reaching behaviour under the robotic IPT, such as lower speed and straighter direction were linked  
61 to reduced body sway. MFR of the contact receiver was influenced by the robotic control mode such as that a  
62 predictive mode reduced movement variability and increased postural stability to a greater extent in comparison  
63 to human IPT. The effects of the reactive robotic system, however, more closely resembled the effects of IPT  
64 provided by human contact provider.

65 **Conclusion**

66 The robotic IPT system was as supportive as human IPT. Robotic IPT seemed to afford more specific  
67 adjustments, such as trading reduced speed for increased accuracy, to meet the intrinsic demands and constraints  
68 of the robotic system. Possibly, IPT provided by a human contact provider reflected reactive interpersonal  
69 postural coordination more similar to the robotic system's follower mode.

70

71 **Keywords:** interpersonal light touch, robotic assistance, body balance, forward reaching

72

73

74 **Précis (<50 words)**

75 Interpersonal touch support by a robotic system was evaluated against support provided a human partner during  
76 maximum forward reaching.

77 Human contact receivers showed comparable benefits in their reaching postural performance between the  
78 support conditions.

79 Coordination with the robotic system, nevertheless, afforded specific adaptations in the reaching behaviour.

80

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81 **Introduction (<4500 words)**

82 If robotic systems are envisaged as the solution to future shortages in clinical staff and caregivers for the  
83 purpose of augmenting of patients' mobility by a provision of balance support, they must show a responsiveness  
84 to the social constraints and demands, which govern any routine physical interaction between a patient and a  
85 human carer. From a scientific and engineering point of view, therefore, the principles of human-human  
86 interactions during physical interactions need to be extracted and evaluated in terms of their transferability to  
87 human-robot interactions as exoskeletal approaches may be unsuitable for frail individuals due the weight added  
88 to the body. In physical rehabilitation, caregivers and therapists routinely provide physical assistance to balance-  
89 impaired individuals during postural mobilization and transfer manoeuvres. In order to prevent long-term habitual  
90 dependency of a patient on external balance aids and other forms of support, a therapist needs to be adopt an  
91 optimum level of postural assistance that maximizes a patient's movement autonomy ('assist-as-needed'). One  
92 possible approach is the provision of deliberately light interpersonal touch (IPT) by a caregiver, which can be  
93 used to reduce body sway in quiet standing in neurological patients with impaired postural stability when  
94 applied to patients' backs (Johannsen, McKenzie, Brown, Redfern, & Wing, 2017). In such an interpersonal  
95 postural context, the contact receivers (CR) experiences haptic contact passively with little or no possibility to  
96 influence the interaction due to their greater motion-task constraints compared to those of the contact provider  
97 (CP). Not only the movement degrees of freedom available to each individual during IPT, but also the relative  
98 postural stability of both partners determines the strength of the IPC and the individual benefit of IPT, with  
99 more enhanced postural stability in the intrincically less stable person (Johannsen, Wing, & Hatzitaki, 2012).  
100 To explore the interdependencies between CR and CP during IPT in more detail, we evaluated performance in  
101 maximum forward reaching (MFR) with and without light IPT applied to the ulnar side of the wrist of  
102 blindfolded CR's extended arm intended to provide a social haptic cue and impose social coordinative  
103 constraints on both the CR and the CP (Steinl & Johannsen, 2017). Interestingly, IPT reduced sway more  
104 effectively when the CP had the eyes closed and their perception of CR's motion was based on haptic feedback  
105 alone. In contrast, IPT with open eyes did not result in reduced sway compared with a condition in which IPT  
106 was not provided (Steinl & Johannsen, 2017). We speculated, therefore, that minimization of the interaction  
107 forces and their variability at the contact location during IPT acts as an implicit task constraint and shared goal  
108 between both partners (Knoblich & Jordan, 2003). This goal might afford predictive sway control in each  
109 individual and consequently led to in-phase interpersonal postural coordination with an average zero lag but also

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110 minimization of the variability of the interaction force (Johannsen, Guzman-Garcia, & Wing, 2009; Johannsen  
111 et al., 2012).

112 In the present study, we intended to contrast the effects of human IPT (hIPT) on CR's postural performance  
113 against the effects of two different modes of robotic IPT (rIPT) and expected specific costs and benefits on body  
114 sway and postural performance due to the robotic response modes. Similar to hIPT, rIPT was applied in a  
115 "fingertip touch" fashion to CR's wrist without any mechanical coupling or weight support. The robotic system  
116 either followed a participant reactively or predicted a participant's movement trajectory. As the coupling  
117 between two humans with IPT in terms of the interaction forces is intrinsically more noisy due to each  
118 individual's motion dynamics and response delays, we expected that a predictive mode of the robotic system  
119 would result in a less noisy haptic coupling and therefore enhance performance in the MFR task, such as greater  
120 reaching distance with less body sway. In addition, the reactive mode of the robot was supposed to be  
121 advantageous over hIPT due to the fixed response delay, which would enable participants to extract own  
122 movement-related information from the interaction forces for balance control.

123

## 124 **Methods**

### 125 *Participants*

126 We tested 10 healthy young adults ( average age=28.5, SD 3.35 years, 3 females and 7 males) as contact  
127 receivers (CR) performing a maximum forward reaching (MFR) task. Participants were not affected by any  
128 neurological or orthopedic indications. Participants were recruited as an opportunity sample from students of the  
129 university. The study was approved by the ethical committee of the medical faculty of the TU Munich and all  
130 participants gave written informed consent.

131

### 132 *Equipment and experimental procedure*

133 One healthy adult, male contact provider (CP) applied the IPT to the wrists of the contact receivers (CR). The  
134 CR stood blindfolded on a force plate (Bertec 4060, Columbus, OH, USA; 500 Hz) in bipedal stance performing  
135 the MFR task. CR was always instructed to reach as far forward as possible by bending the torso but not the  
136 knees. Before the start of a trial, CR was instructed to stand in a relaxed manner, the right arm extended at  
137 shoulder height to reach horizontally above a height-adjusted table. After the start of a trial, CR was instructed  
138 to remain static for at least 5 seconds (baseline) until an auditory signal cued the start of the MFR task (Fig. 1a).  
139 During IPT, CP stood facing orthogonally to CR in bipedal stance between CR's force plate and the table,

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140 parallel to the reaching direction. CP provided IPT with the right extended arm by lightly contacting the wrist at  
141 its ulnar side of the CR. During IPT, CP kept the eyes open to receive visual cues of a CR's motion as would  
142 the robotic systems by optical motion tracking. During the robotic IPT conditions, a single KUKA LWR4+  
143 manipulator (Augsburg, Germany) served as CP. The CP kept light contact with CR's ulnar side of the wrist.  
144 CR's body sway was determined in terms of the anteroposterior (AP) and mediolateral (ML) components of the  
145 Center of Pressure (CoP), as derived from the six components of the ground reaction forces and moments.  
146 In in the human-robot interaction conditions, the CR's wrist was tracked by the end effector of the robotic  
147 system without any mechanical coupling (Fig. 1b). The robotic system provided contact via a hemispherical  
148 rubber pad attached to a force sensor (OptoForce 3D OMD, OnRobot, Odense, Denmark; 500 Hz) on the end-  
149 effector, which kept the relative orthogonal distance constant. The force sensor was used to measure force at the  
150 contact location. The CR's wrist position, required to control the robotic system, was measured by an  
151 optoelectronic motion capture system (OptiTrack, NaturalPoint, Corvallis, OR, USA; 100 Hz). To provide  
152 nearly the same feeling for the CR in both touch conditions, the CP was wearing a thin rubber glove to provide  
153 similar tactile sensation to the case of rIPT where the end effector of the robot had a rubber surface (Fig. 1b).  
154 Participants' movements of the right hand were tracked with a marker-based optical motion capture system by  
155 placing three reflective markers on the right hand (one on the caput ulnae/processus styloideus radii/basis and  
156 two on the ossa metacarpi). Tracked hand position was sent to the robot to control the robots' movements but  
157 also recorded to calculate reaching distance in the MFR end-state. The robotic control scheme required high  
158 control frequencies to avoid unstable behaviors (Siciliano, Sciavicco, Villani, & Oriolo, 2009). For this reason,  
159 the robot was controlled at 500 Hz. Interaction forces were measured at the same frequency of 500 Hz, while the  
160 CR's hand was tracked at 100 Hz. Hence, it was necessary to up-sample the motion tracking system to match  
161 the robot control frequency.

162 This experiment contrasted three modes of IPT provision: hIPT, robotic light interpersonal touch with reactive  
163 following of the participant's movements (rIPTfollow), robotic light interpersonal touch with anticipation of the  
164 participant's movements (rIPTanticip). Robotic IPTfollow and rIPTanticip were both provided through an  
165 artificial "finger" with optical tracking of the CR's wrist and control of the contacting force. The three IPT  
166 conditions were assessed in blocks of 5 trials. The order of the blocked conditions was fully randomized, and  
167 each single trial lasted 20 s. Out of a total of 150 trials, 11 trials failed to track the CR's hand and are excluded  
168 from the analysis.

169

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170 --- insert Figure 1 about here ---

171

### 172 *Data reduction*

173 All data post-processing was conducted in Matlab 2016b (Mathworks, Natick, MA, USA). Kinematic and force-  
174 torque sensor data were spline-interpolated to 600 Hz and subsequently merged with the force plate recordings.  
175 The data was smoothed using a generic dual-pass, 4<sup>th</sup> order Butterworth low-pass filter with a cut-off frequency  
176 of 10 Hz. CoP and marker data were differentiated to yield velocity. Subsequently, trials were segmented into  
177 three phases of the MFR (baseline phase, reaching phase, and MFR end-state) based on the AP position of CR's  
178 wrist marker as described in Steidl and Johannsen (Steidl & Johannsen, 2017) (Fig. 2).

179

180 --- insert Figure 2 about here ---

181

182 To investigate the effects of IPT on human CR's postural performance during the maximum forward reaching  
183 (MFR) task, MFR amplitude in the horizontal plane was determined from the difference of the wrist's average  
184 position in the baseline phase and in the MFR end-state. The angular deviation of a straight line connecting  
185 these two positions from the AP axis, the path length and normalized path length (path length/amplitude) of the  
186 reaching trajectory, the average and summed as well as the standard deviation of the orthogonal deviation of the  
187 trajectory from a straight line and the average and peak velocity of the wrist during the reaching phase were  
188 extracted. Body sway in the baseline, reaching phase as well as in the MFR end-state was extracted as the  
189 standard deviation of the COP velocity (SD dCoP) in AP and ML directions. In order to quantify the efficiency  
190 of balance control during the MFR reaching phase and evaluate a potential speed-accuracy tradeoff, we  
191 calculated an Index of Performance (IoP) for both sway directions based on a modification of Fitts and  
192 Peterson's index (Bootsma, Fernandez, & Mottet, 2004; Fitts & Peterson, 1964). Our IoP associated the time for  
193 the reaching movement (MT) with the difficulty of the MFR (IoD) in terms of the achieved maximum amplitude  
194 (A) and the variability of sway in the reaching phase (S) as the effective precision constraint:

$$\text{Index of Difficulty (IoD)} = \log_2 \left( \frac{A}{4.133 * S} + 1 \right)$$

$$\text{Index of Performance (IoP)} = \frac{\text{IoD}}{\text{MT}}$$

195 The unit of the IoP is bit/s and thus expresses the informational "throughput" of a participant during the  
196 movement.

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### 198 *Statistical analysis*

199 SPSS version 23 (IBM, Armonk, NY, USA) was used for statistical analysis. All outcome parameters were log-  
200 linearized before statistical analysis to approximate normal distribution. A linear mixed model with IPT  
201 condition as within-subject factor including participant as random effect was applied using maximum likelihood  
202 estimation. To test for statistical significance, an alpha level of 0.05 was used and post-hoc comparisons were  
203 computed as required to distinguish between IPT conditions.

204

### 205 *Robotic control*

206 Both the robot end-effector position and the interaction force were actively controlled using a hybrid force-  
207 position controller, which was based on the prediction of the CR's wrist motion. A Linear Kalman Filter (LKF)  
208 (Kalman, 1960) with a constant velocity model was exploited to generate a reference for the participant's wrist  
209 trajectory. A constant velocity LKF assumes that the motion is generated by the discrete linear system

$$210 \quad s(t+1) = \begin{bmatrix} p_{KF}(t+1) \\ v_{KF}(t+1) \end{bmatrix} = \begin{bmatrix} I & \Delta t I \\ 0 & I \end{bmatrix} \begin{bmatrix} p_{KF}(t) \\ v_{KF}(t) \end{bmatrix} + \eta = Fs(t) + \eta,$$

211 where the state vector  $s(t)$  contains the Kalman-estimated wrist position  $p_{KF}(t)$  and velocity  $v_{KF}(t)$ ,  $I$  is an  
212 identity matrix,  $\Delta t$  is the sampling time, and  $\eta$  is an additive Gaussian noise. The LKF predicts the next state  
213  $s_{KF}(t) = [p_{KF}(t)^T \ v_{KF}(t)^T]^T = Fs(t-1) + y(t)$ , where the correction term  $y(t)$  is computed as in [56] and it  
214 depends on the measured wrist position. In our setup, the correction term was set to  $y(t) = 0$  until a new  
215 measure of the wrist position was available. In this way, the predicted position  $p_{KF}(t)$  was generated at 500 Hz  
216 and used to control the robotic system. The LKF was exploited to realize two different robotic modes, i.e. the  
217 robotic follower and the robotic anticipatory modes. More specifically, in the rIPTfollow mode the robot  
218 passively followed the wrist motion while providing a light touch. To implement a passive follower, the position  
219  $p_{KF}(t)$  (Position Error: rIPTfollow AP – 0.010218m, ML – 0.004994 m) (Fig. 3b) predicted by the LFK at the  
220 actual time instant  $t$  was used to generate the control command described in the previous section. In this way,  
221 the robotic system followed the wrist position with one sample delay (10 ms). In the rIPTanticip mode, the robot  
222 predicted the future wrist position to lead the motion while providing a light touch. To realize the leading mode,  
223 the LKF was exploited to make a one-step prediction of the wrist position. In particular, the predicted future  
224 position  $p_{KF}(t+1) = F P_{KF}(t)$  (Position error: rIPTanticip AP – 0.012256, ML – 0.007164 m) (Fig. 3a) was  
225 used to generate the control command. In this way, the robot was anticipating the human motion by one sample  
226 (10 ms), thereby leading the movement execution.



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227 During the MFR task, the robotic system provided a light touch along the contact directions, while predicting  
228 and following (or predicting) the participant's right wrist trajectory in the AP direction. The robotic system was  
229 controlled to exert a maximum of 1 N force along the ML and vertical directions (force-controlled directions),  
230 while tracking the hand motion along the AP axis (position-controlled direction). The force  
231  $f_m = [f_{m,x} \ f_{m,y} \ f_{m,z}]^T$  measured at the contact point and the CR's Kalman-estimated wrist position  $p_{KF} =$   
232  $[p_{KF,x} \ p_{KF,y} \ p_{KF,z}]^T$  were used to define the desired position of the robot end-effector as  $p_x = p_{KF,x} + k_f(f_{m,x} -$   
233  $f_{des})$  and  $p_z = p_{KF,z} + k_f(f_{m,z} - f_{des})$ . The desired contact force  $f_{des}$  was set to 0.3 N and the gain  $k_f$  was set  
234 to 0.00004 m/N, thus regulating the robot motion at the speed of 2.5 mm/s for  $f_{m,i} - f_{des} = 1\text{ N}$  at the 500 Hz  
235 update cycle. For the AP direction, the desired robot position was  $p_y = p_{KF,y}$ . Roughly speaking, the presented  
236 controller was adding a delta of position  $k_f(f_m - f_{des})$  to ML and vertical directions if the measured force was  
237 different than  $f_{des} = 0.3\text{ N}$ . If the measured force was larger than 0.3 N, the delta of position was negative and  
238 the robot moves slightly back to reduce the force. If the measured force was smaller than 0.3 N, the delta of the  
239 position was positive and the robot pushed slightly against CR's wrist to remain in contact. In this way, the end-  
240 effector kept in contact with the user's wrist while maintaining low interaction forces. The forces were not  
241 different between the two rIPT modes. As expected, the average contact force was close to the prespecified  
242 value of 0.3N (average force=0.32N, SD 0.09).

243

244

--- insert Figure 3 about here ---

245

## 246 **Results**

247 Table 1 summarizes all statistical comparisons. The MFR amplitude in the horizontal plane was not affected by  
248 the IPT condition. All three IPT conditions resulted in comparable amplitudes (hIPT: mean=35.8 cm, SD 1.5;  
249 rIPTanticip: mean=35.4 cm, SD 1.4; rIPTfollow: mean=35.1 cm, SD 1.5). Average (Fig. 4a) and peak planar  
250 reaching velocity (Fig. 4b) were slower in both rIPT conditions compared to hIPT. The directional angle of  
251 reaching in the horizontal plane was more straight ahead in the rIPTfollow condition (AV angle=-0.83 deg,  
252 SEM 1.84) and a tendency of less lateral drift in rIPTanticip (AV angle=-1.34 deg, SD 1.92) compared to hIPT  
253 (AV angle=-4.55 deg, SD 2.12). Orthogonal deviation from a straight line, in terms of both the average (Fig. 4c)  
254 and summed deviation (Fig. 4d) as well as the variability, was lower in hIPT than rIPTanticip. Path length was  
255 not altered by the IPT conditions but the normalized path length indicated less curvature in rIPTfollow  
256 compared to rIPTanticip (Fig. 4e).

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258

--- insert Figure 4 about here ---

259

260 Sway variability in either the AP or ML directions was not different between the three IPT conditions in the  
261 baseline phase and the MFR end-state. During the reaching phase, however, AP sway variability was reduced in  
262 both conditions involving rIPT compared to hIPT (Fig. 5a) and rIPTanticip compared to rIPTfollow. In contrast  
263 , only rIPTanticip showed reduced ML sway variability compared to hIPT (Fig. 5b).

264 The IoD differed between the three conditions in the AP direction., with the lowest scores in hIPT compared to  
265 both rIPT conditions. In the ML direction, hIPT had a lower IoD score compared to rIPTanticip only (Fig. 5c).

266 In contrast, no difference in the informational “throughput” (IoP) was observed between the three conditions  
267 (Fig. 5d).

268

269

--- insert Figures 5 about here ---

270

271

## 272 **Discussion**

273 Our study contrasted the effects of deliberately light interpersonal touch received by a robotic system on the  
274 control of movements and body balance during maximum forward reaching in healthy young adults. Changes in  
275 spontaneous MFR behaviour and body sway were assessed as a function of the robotic system’s mode of control  
276 (follower vs anticipation) with respect to CR’s movements. With respect to the body sway in the MFR baseline  
277 or end-state as well as the achieved MFR amplitude, rIPT was as efficient as hIPT. The observed changes in  
278 reaching behaviour with rIPT coincided with reductions in body sway during the reaching phase in the same  
279 condition: rIPTanticip provided the best stabilization of all three IPT conditions. The Index of Difficulty  
280 indicated increased behavioural difficulty in the two robotic conditions compared to hIPT, despite the fact that  
281 the Index of Performance indicated similar informational throughput between the three conditions. On a  
282 qualitative level, however, rIPTfollow resulted in intermediate behavioural alterations, less different to hIPT  
283 than rIPTanticip. This observation might imply that in hIPT the human contact provider coordinated the  
284 movements in a reactive fashion as well, potentially in follower mode due to visual dominance or as the more  
285 optimal strategy due to the inability to stem the computational complexity of predicting CR’s trajectory.

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286 In our current study, the provision of IPT by the CP involved visual feedback of CR and his or her  
287 movements. As this would be more similar to the optical tracking of CR's motion used by the robotic system. In  
288 human pairs, the presence of visual feedback with habitual visual dominance is likely to turn the CP into a  
289 follower of CR's movement (Steinl & Johannsen, 2017). Assessing HHI as well as HRI in a single degree of  
290 freedom object manipulation task, Groten et al. (Groten, Feth, Goshy, et al., 2009; Groten, Feth, Klatzky, Peer,  
291 & Buss, 2009) characterized inter-agent dominance as a function of the interaction force with dominance  
292 varying flexibly between both partners in a joint action. Generally speaking, in most physical interactions  
293 between two human individuals leader-follower relationships are not necessarily fixed. It seems to be the case,  
294 however, that the more adaptive individual, for example the person on whom fewer requirements to fulfill  
295 specific movement constraints are imposed, is more likely to take a follower role (Skewes, Skewes, Michael, &  
296 Konvalinka, 2015).

297 Despite impressive advances in the recent decade, current robotics engineering is still distant from developing  
298 robotic systems able to assist human individuals socially, especially during postural activities and balance  
299 exercises (Sheridan, 2016). In the both rIPT conditions of the current study, the dynamics of the robotic system  
300 were not independent but in one way or another a direct consequence of CR's movements. Despite the lack of  
301 any real "social cognitive" capabilities of the robotic system, this fact can nevertheless be interpreted as highly  
302 precise responsiveness, which a real human CP could never match. We assume that participants were not able to  
303 consciously perceive any difference between the anticipatory and follower rIPT modes, just an absolute timing  
304 difference of 20 ms, and therefore would not change their behaviour voluntarily. Possibly due to a shift in  
305 participants from less to more reactive, feedback-dependent postural control, CRs reduced their reaching  
306 velocity to adjust their movements more precisely to the current position of the robotic end-effector and for the  
307 same to stay in contact with their wrist. These concerns could have been even more prominent in the rIPTanticip  
308 condition than in rIPTfollow.

309

### 310 *Reaching performance and body sway*

311 An increased MFR amplitude would demonstrate improved confidence in the ability of keeping own body  
312 balance stable while approaching one's forward limits of stability (Duncan, Weiner, Chandler, & Studenski,  
313 1990; Maki & McIlroy, 2006). As we did not observe any difference in reaching amplitude between all three  
314 forms of IPT, it means that IPT provided by a robotic system does not disrupt or distract the human CR. During  
315 the reaching phase, the facilitation of stabilization of body sway by rIPT tended to surpass the effect of hIPT,

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316 especially in a robotic control mode involving anticipation. This shows that rIPT does not destabilize CR's  
317 postural behaviour but can lead to a further reductions in behavioural variability. Nevertheless, human CRs  
318 altered their MFR behaviour when IPT was provided not by the human partner but by the robotic system. The  
319 most obvious changes were general reductions in the average and peak planar MFR velocity with rIPT. As body  
320 sway tended to be reduced in these situations, these adjustments to the robotic CP could reflect a trade-off  
321 between speed and accuracy [Fitts, 1954]. According to this interpretation, participants may have effectively  
322 controlled sway variability in order to meet any perceived difficulty increase in rIPT resulting from "hardware"  
323 constraints imposed by technical limitations of the robotic system and "soft" constraints in terms of fulfilling the  
324 task goal of MFR with rIPT support (Bardy, Marin, Stoffregen, & Bootsma, 1999; Scholz & Schoner, 1999).  
325 "Assist-as-needed" (Cai et al., 2006) robotic devices will provide corrective forces only if a participant's limb  
326 movement kinematics hit the walls of a predefined "virtual tunnel" (Duschau-Wicke, von Zitzewitz, Caprez,  
327 Luenenburger, & Riener, 2010). These "patient-cooperative" robotic assistive devices may improve the outcome  
328 of gait training but also body balance in stroke rehabilitation (Srivastava et al., 2015; Srivastava et al., 2016).  
329 Assist-as-needed robotic approaches translate into corrective forces keeping an individual's body or limbs  
330 within an initially defined "normal" range. In contrast to such "positive" force feedback, in which a robotic  
331 system aims to guide a participant's limb along a specific trajectory by applying a corrective force, our  
332 deliberately light interpersonal touch paradigm could be described to act with "negative" force feedback. This  
333 means that if participants stray from a reaching trajectory, they will perceive a momentary reduction in touch,  
334 which might cue them to perform a subtle correction with the intention to minimize contact force variability.  
335 The robotic system in our study was controlled according to this principle, and we believe it imitated CR's  
336 behaviour more naturally. At the same time, the reaching trajectory was not prespecified within the robotic  
337 system but emerged as a compromise between the CR and the respective CP. In this sense, the CR's movement  
338 range remains completely unconstrained. Any constraints result from the "social" context of the HHI or HRI  
339 system.

340

### 341 *Human-robotic movement coordination*

342 Haptic interactions between caregiver and patient play an prominent role in cooperative and collaborative  
343 human-human sensorimotor interactions in physical rehabilitation (Sawers & Ting, 2014). More recently,  
344 Haarman et al. (Haarman et al., 2017) investigated the balance-assistive forces applied by therapists to the pelvis  
345 of patients during gait training. Using force-torques sensors, they quantified the predominant corrective forces

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346 applied by the therapists in the mediolateral direction to both sides of the hips at about 9N, amounting to  
347 approximately 2% of participants' body weight. Compared to the forces imposed by the robotic systems in our  
348 current study, the forces applied by the therapists are still magnitudes greater.

349 In a cooperative physical HHI, the relationship between interaction forces and movement kinematics is  
350 important for communicating intended movement direction (Mojtahedi, Whitsell, Artemiadis, & Santello, 2017;  
351 Sawers et al., 2017; Takagi, Usai, Ganesh, Sanguineti, & Burdet, 2018). Gentry and Murray-Smith (Gentry &  
352 Murray-Smith, 2003) described the influence of haptic signals used for coordination and synchronization in  
353 human dancing. Hoelldampf et al. (Hoelldampf, Peer, & Buss, 2010) used interaction forces to adjust and  
354 optimize the robot's motion in a system designed for human-robot interactive dancing. Similarly, Chen et al.  
355 (Chen et al., 2017; Chen et al., 2015) developed a mobile robotic system responsive to interaction forces to  
356 practice dance stepping with a human partner. Response gain and compliance of the robot's effectors altered  
357 human upper body posture and human-robot coordination. Interestingly, the majority of human partners  
358 perceived the robots as following their movements (Chen et al., 2015).

359 In this context it is remarkable that rIPTfollow led to the straightest forward reaching trajectories with least  
360 amount of medial drift. This could mean that a robotic system that emphasizes a reactive follower strategy is a  
361 better haptic "communicator" in the sense that it made participants to "listen" more closely to the haptic  
362 feedback they received. Possibly, participants interpreted rIPT as more reliable as a relative spatial reference and  
363 therefore adjusted their reaching movements more in a feedback-driven manner. In contrast, although  
364 rIPTanticip also tended towards a more straight ahead reaching movement, the condition showed the greatest  
365 and most variable orthogonal deviation from a straight line connecting the start and end point. The robotic  
366 system in leader mode could have actually "misguided" participants in the sense, that it tried to anticipate a  
367 participant's next position and so reinforced a participants' tendency to deviate from their current trajectory.

368 That this interaction did not cause excessive deviations of the reaching trajectory could be a result of the tighter  
369 bounds applied to variability of body sway in rIPTanticip.

370 Mohan et al. (Mohan, Mendonca, & Johnson, 2017) assessed the interactions between a therapist and a stroke  
371 patient in the less complex situation of raising and drinking from a cup with the assistance of the therapist. By  
372 analyzing the both partners' movement kinematics, they concluded that the strength of the interpersonal  
373 coupling varied as a function of the task's phase with stronger interaction at the beginning and the end of the  
374 action (Mohan et al., 2017). In our current study, the robotic system operated in a single control mode  
375 throughout an entire trial. In terms of shaping the participants' MFR behaviour it might be even more optimal, if

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376 the robotic system had switched from a leader mode in the baseline phase and the end-state to a follower mode  
377 during the reaching phase.

378

## 379 Conclusions

380 Beneficial deliberately light interpersonal touch for balance support during maximum forward reaching is easily  
381 provided by a robotic system even when it is mechanically uncoupled to the human contact receiver. This effect  
382 does not rely on the system's capability to predict the future position of the contact receiver's wrist. The effects  
383 the uncoupled robotic IPT in reactive following mode were comparable to human IPT on most parameters. As  
384 the robotic system itself was not designed for any form of "social" cognition or explicit haptic communication,  
385 our study nevertheless demonstrates that robotic IPT can be used to implicitly "nudge" human contact receivers  
386 to alter their postural strategy for adapting to the robotic system without any decrements in their postural  
387 performance during maximum forward reaching.

388

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389 **Acknowledgements**

390 We thank Prof. G. Cheng, Prof. M. Buss, Prof. S. Hirche, Dr. K. Ramirez–Amaro, and J. R. Guadarrama Olvera  
391 for providing the experimental infrastructure and S. M. Steinl and M. Langer for their involvement in data  
392 acquisition. Funding: we acknowledge the financial support by the federal Ministry of Education and Research  
393 of Germany (BMBF; 01EO1401), the Deutsche Forschungsgemeinschaft (DFG) through the TUM International  
394 Graduate School of Science & Engineering (IGSSE), German Academic Exchange Service (DAAD), and  
395 Helmholtz Associate.

396

397 **Author contributions**

398 K.P. analyzed datasets for the experiment, interpreted results, and wrote the paper. S.E., and H.S. designed and  
399 performed the experiment, interpreted results, and wrote the paper. M.S. designed and performed the  
400 experiment, interpreted results, and wrote the paper. L.J. and D.L. designed the experiment, interpreted results,  
401 and wrote the paper.

402

403 **Conflicts of interest**

404 The authors declare that they have no conflict of interest.

405

406 **Key points**

- 407 1. Robotic light touch supports human balancing performance  
408 2. Human participants adapt to the specific affordances of robotic light touch support  
409 3. Subtle differences in the robotic modes of interaction have behavioural effects on the human performer

410

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494 **Tables**

495 **Table 1.** Summary of all statistical comparisons. IPT: interpersonal touch; hIPT: human IPT; rIPT anticip:  
 496 robotic IPT anticipating; rIPT follow: robotic IPT following; SD dCoP: standard deviation of Centre-of-Pressure  
 497 velocity; AP: anteroposterior; ML: mediolateral; MFR: maximum forward reach. +: marginally significant; n.s.:  
 498 not significant.

	Variable	Main effect	Pairwise Comparison		
		IPT condition	hIPT vs rIPT anticip	hIPT vs rIPT follow	rIPT anticip vs rIPT follow
		F; p	p		
Reaching performance	Reaching amplitude	0.50; 0.62	n.s.	n.s.	n.s.
	Angular deviation	3.35; 0.07+	0.06+	0.03	n.s.
	Path Length	1.28; 0.31	n.s.	n.s.	n.s.
	Normalized path length	3.67; 0.06	n.s.	n.s.	0.04
	AV orthogonal deviation	2.73; 0.12	0.03	n.s.	n.s.
	SD orthogonal deviation	8.34; 0.005	0.001	n.s.	n.s.
	Σ Orthogonal deviation	3.17; 0.09	0.04	n.s.	n.s.
	AV hand velocity	12.95; 0.001	0.03	0.001	n.s.
	SD hand velocity	27.57; <0.001	<0.001	n.s.	n.s.
Peak hand velocity	16.42; 0.001	<0.001	0.005	n.s.	
Body sway (SD dCoP)	Baseline (AP)	1.58; 0.25	n.s.	n.s.	n.s.
	Baseline (ML)	1.09; 0.36	n.s.	n.s.	n.s.
	Reaching (AP)	11.07; 0.004	0.001	0.009	0.05
	Reaching (ML)	5.03; 0.05	0.02	n.s.	n.s.
	MFR end-state (AP)	0.32; 0.73	n.s.	n.s.	n.s.
	MFR end-state (ML)	0.99; 0.40	n.s.	n.s.	n.s.
Index of Difficulty	AP	11.07; 0.004	0.009	0.002	n.s.
	ML	2.53; 0.13	0.05	n.s.	n.s.
Index of Performance	AP	1.44; 0.28	n.s.	n.s.	n.s.
	ML	2.50; 0.13	n.s.	0.06+	n.s.

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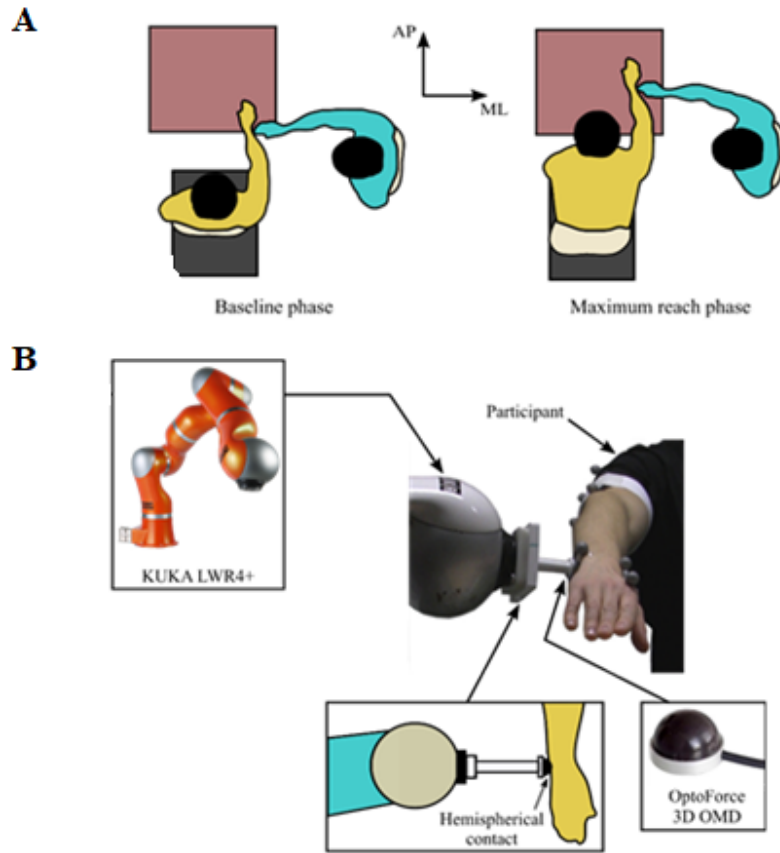
501 **Figures and legends**

502

503 Figure 1. Experimental setup. (A) Execution of the maximum forward reach task with human interpersonal

504 touch (hIPT) support.

505



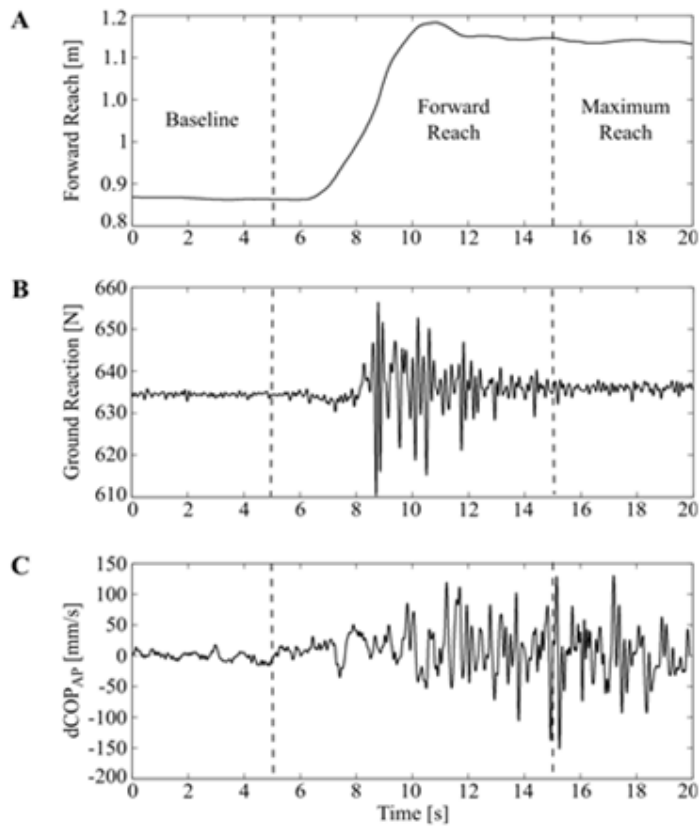
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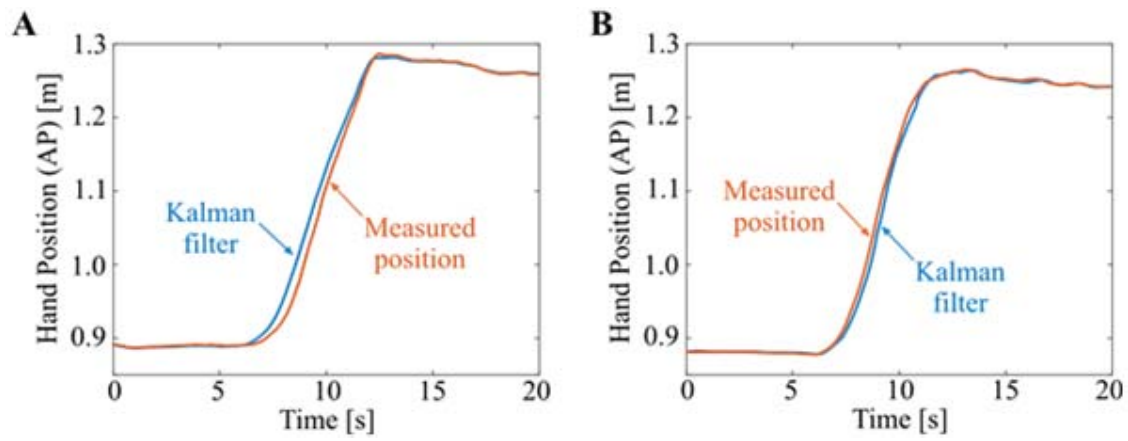
509 Figure 2. Typical profiles of the kinematic and dynamic variables. (A) Forward reaching of the hand marker  
510 divided into three phases. (B) Ground Reaction Force in the vertical direction. (C) Centre-of-Pressure velocity  
511 (dCoP) in the anteroposterior (AP) direction.  
512



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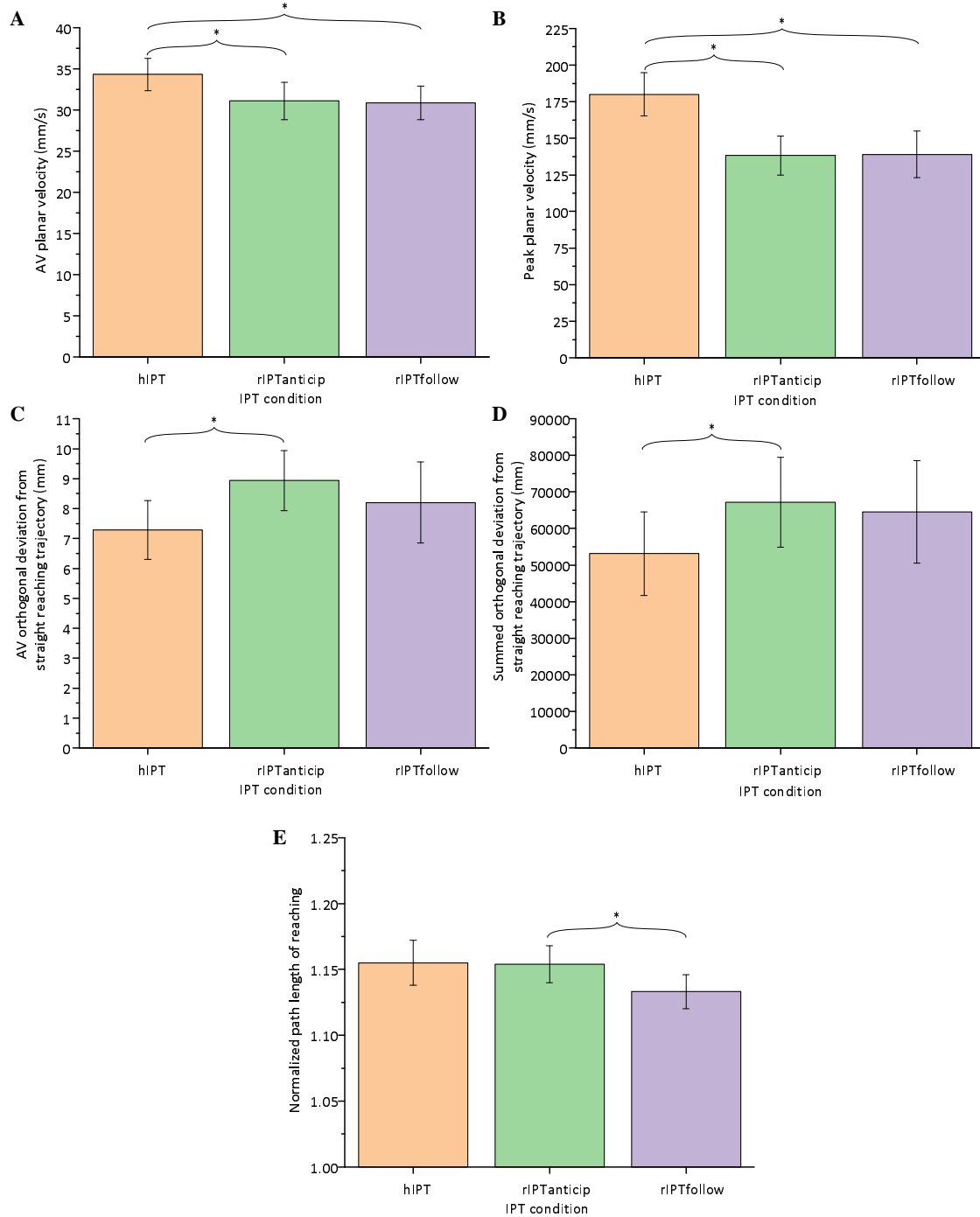
515 Figure 3. Kalman filtered hand position during maximum forward reaching (MFR). (A) Predicted and measured  
516 hand position during MFR for anticipatory robotic interpersonal touch (rIPT) in the anteroposterior (AP)  
517 direction. (B) Estimated and measured hand position during MFR for rIPT in follower mode in the AP direction.



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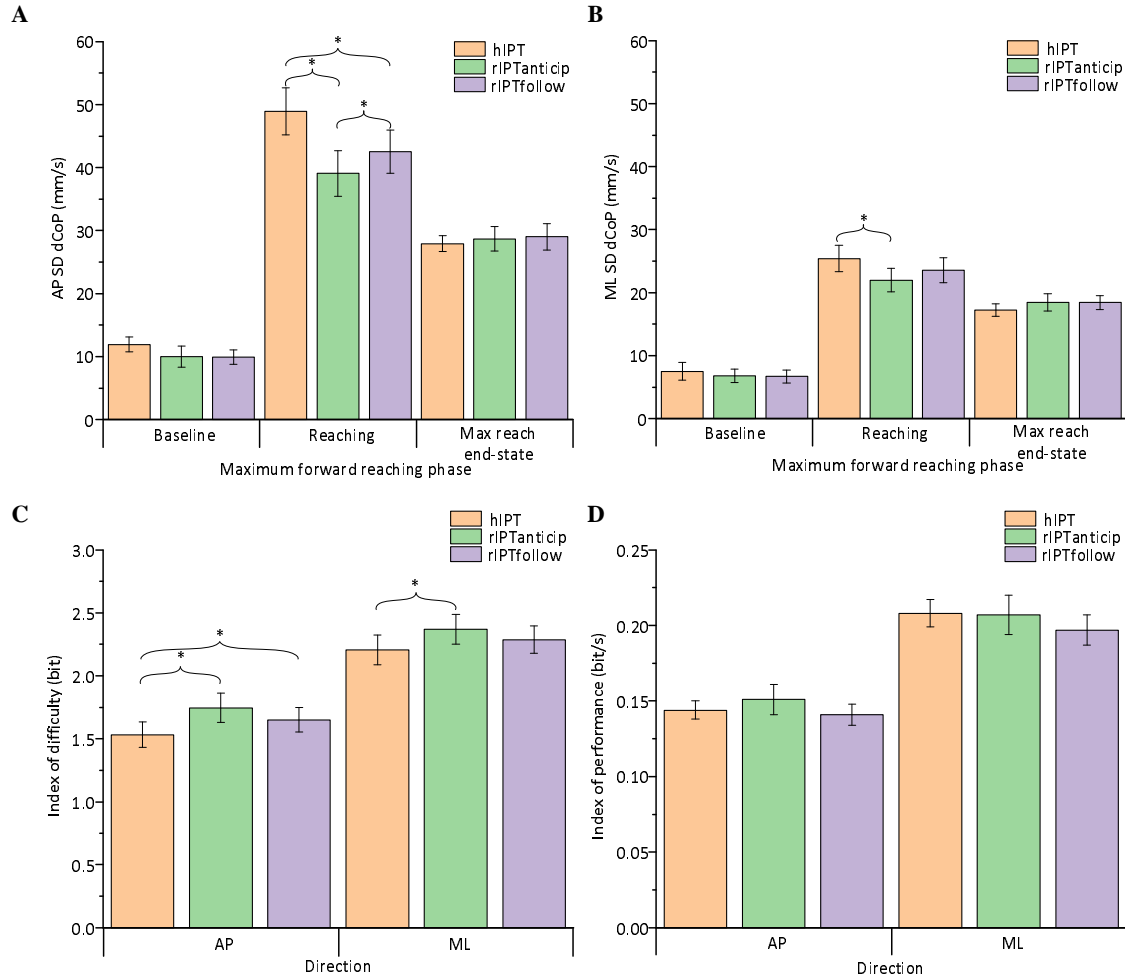
520 Figure 4. Parameters of reaching performance as a function of the interpersonal touch (IPT) condition: (A)  
521 average planar velocity, (B) peak planar velocity, (C) average orthogonal deviation from a straight line linking  
522 the start to the end positions, (D) summed orthogonal deviation from a straight line, (E) normalized path length  
523 of reaching. Error bars show the standard error of the mean across participants. Horizontal brackets indicate  
524 significant within-subject post-hoc single comparisons ( $p < 0.05$ ). hIPT: human IPT; rIPTfollow: robotic IPT in  
525 follower mode; rIPTanticip: anticipatory robotic IPT.  
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529 Figure 5. Body sway in terms of the standard deviation of Centre-of-Pressure velocity (SD dCoP) as a function  
530 of the interpersonal touch (IPT) condition in the anterior-posterior (A) and mediolateral (B) direction in all three  
531 phases of the Maximum Forward Reaching (MFR) task. Index of difficulty (C) and Index of performance (D) in  
532 each IPT condition for both directions. Error bars show the standard error of the mean across participants. Full  
533 horizontal brackets indicate significant within-subject post-hoc single comparisons ( $p < 0.05$ ). hIPT: human IPT;  
534 rIPTfollow: robotic IPT in follower mode; rIPTanticip: anticipatory robotic IPT.  
535



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537