1 # Robotic light touch assists human balance control

2 # during maximum forward reaching

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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 extend 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

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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

3

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 maneuvres. 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 deliberrately 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 individiual 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

4

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.

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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, 4th 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 Steinl and Johannsen (Steinl & 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:

$$Index\ of\ Difficulty\ (IoD) = \log 2 \left(\frac{A}{4.133 * S} + 1 \right)$$

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

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

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, Δt is the sampling time, and η is an additive Gaussian noise. The LKF predicts the next state

213    $s_{KF}(t) = [p_{KF}(t)^{\mathrm{T}} \ v_{KF}(t)^{\mathrm{T}}]^{\mathrm{T}} = Fs(t-1) + y(t)$, 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.

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 $f_{m,i} - f_{des} = 1N$ 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 $f_{des} = 0.3$ 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).

257

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 ---

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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.

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 contraints 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 individudals 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 preceive 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 differene 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 "Asssist-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

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 reveicer. 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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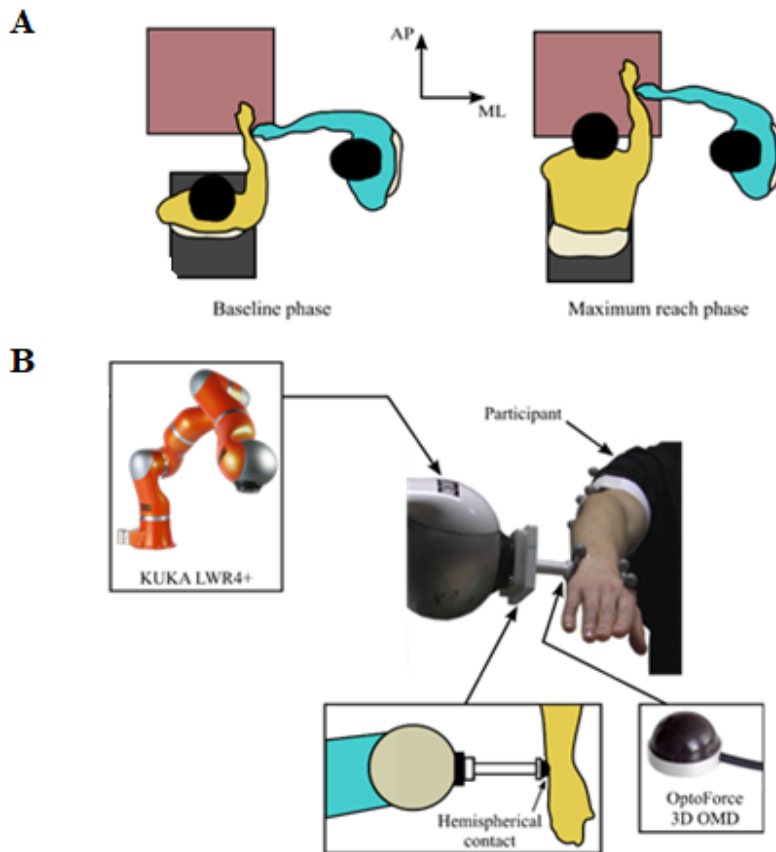Robotic light touch assists balance

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. (B) Robotic IPT without mechanical coupling in hybrid force-position control.
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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
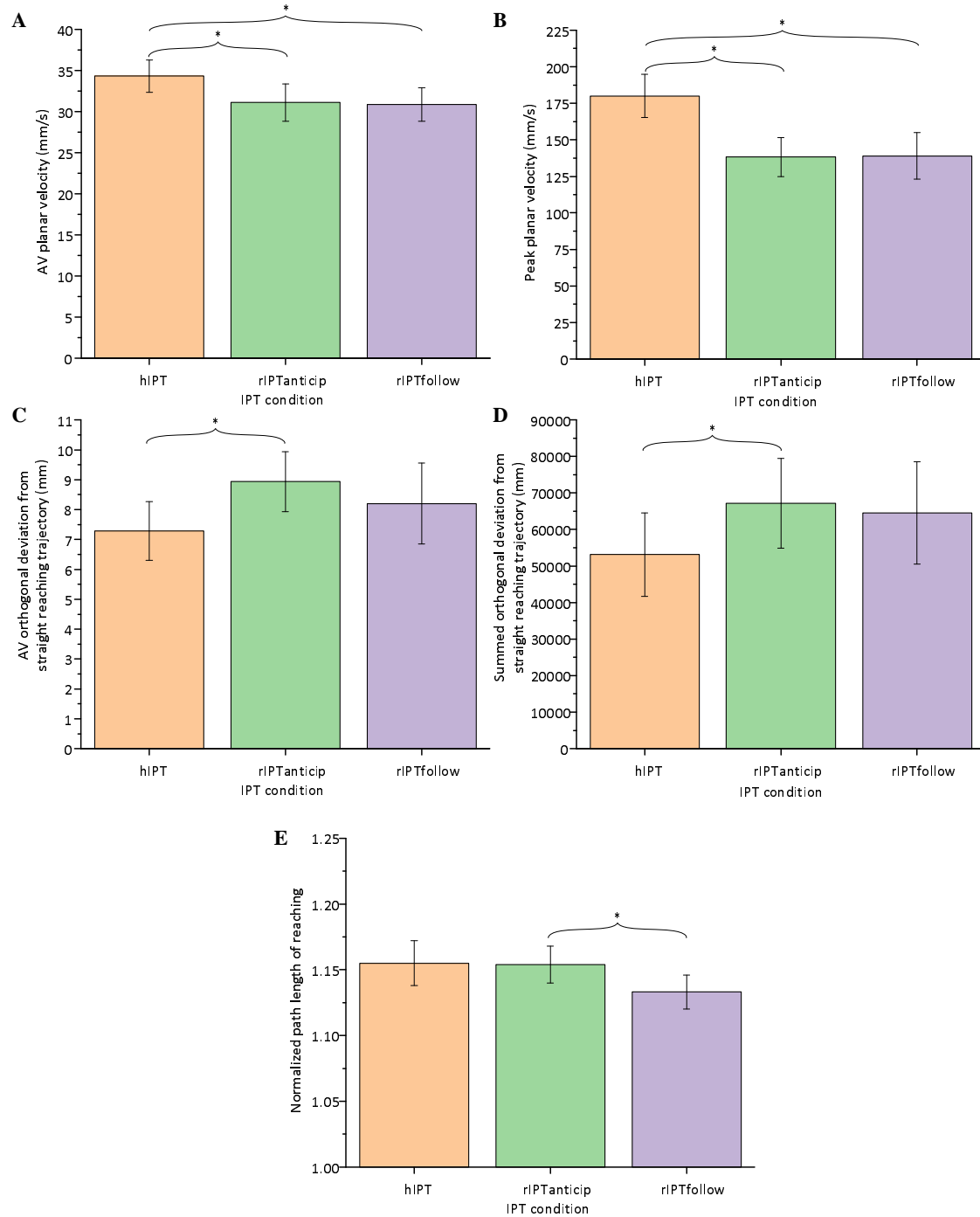511 (dCoP) in the anteroposterior (AP) direction.
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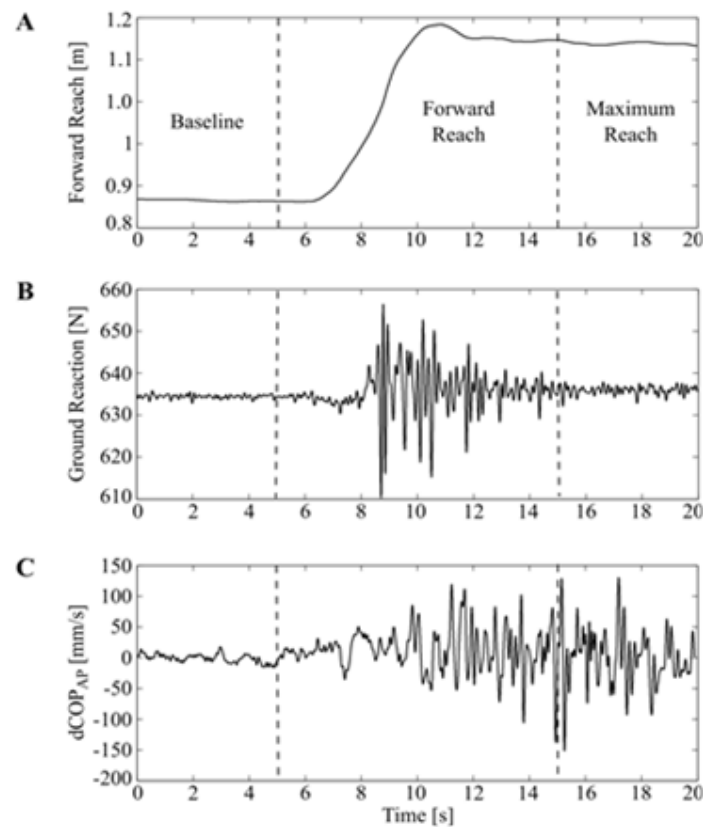
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515   Figure 3. Kalman filtered hand position during maximum forward reaching (MFR). (A) Predicted and measured
516   hand position during MFR for anticipatory robotic interpersonal touch (rIPT) in the anteroposterior (AP)
517   direction. (B) Estimated and measured hand position during MFR for rIPT in follower mode in the AP direction.

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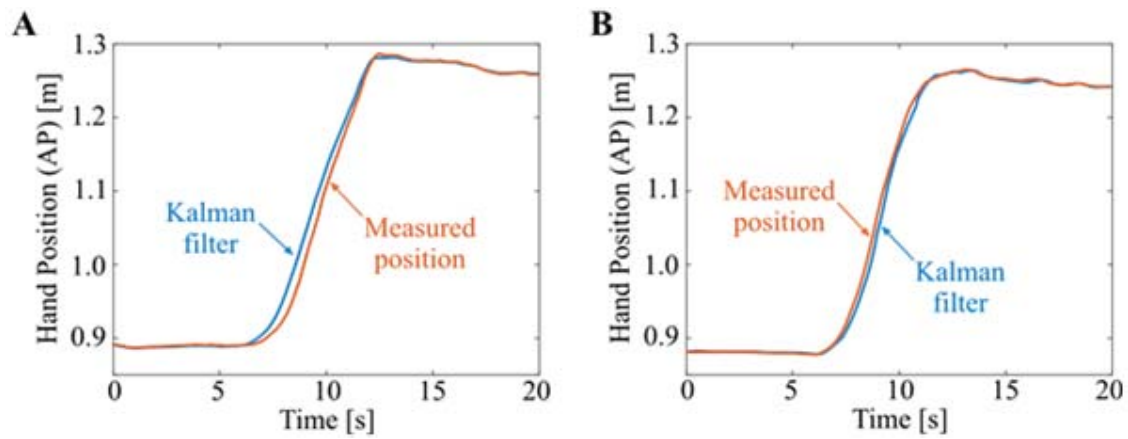
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Figure 4. Parameters of reaching performance as a function of the interpersonal touch (IPT) condition: (A) average planar velocity, (B) peak planar velocity, (C) average orthogonal deviation from a straight line linking the start to the end positions, (D) summed orthogonal deviation from a straight line, (E) normalized path length of reaching. Error bars show the standard error of the mean across participants. Horizontal brackets indicate significant within-subject post-hoc single comparisons (p<0.05). hIPT: human IPT; rIPTfollow: robotic IPT in follower mode; rIPTanticip: anticipatory robotic IPT.

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Figure 5. Body sway in terms of the standard deviation of Centre-of-Pressure velocity (SD dCoP) as a function of the interpersonal touch (IPT) condition in the anterior-posterior (A) and mediolateral (B) direction in all three phases of the Maximum Forward Reaching (MFR) task. Index of difficulty (C) and Index of performance (D) in each IPT condition for both directions. Error bars show the standard error of the mean across participants. Full horizontal brackets indicate significant within-subject post-hoc single comparisons (p<0.05). hIPT: human IPT; rIPTfollow: robotic IPT in follower mode; rIPTanticip: anticipatory robotic IPT.