Contrasting effects of finger and shoulder interpersonal light touch on standing balance

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J Neurophysiol 107: 216–225, 2012. First published September 28, 2011; doi:10.1152/jn.00149.2011.—Sway is reduced by light nonsupporting touch between parts of the body and a fixed surface. This effect is assumed to reflect augmentation of sensory cues for sway by point-of-contact reaction forces. It has been shown that movement of the contact surface can increase sway relative to an earth-fixed contact. Light touch contact with another person, for example, holding hands, affords a moving contact due to partner sway. We asked whether interpersonal light touch (IPLT) would increase sway relative to standing alone. We expected effects on sway to vary as a function of the site of contact and the postural stability of each partner. Eight pairs of participants, standing in either normal bipedal or tandem Romberg stance with eyes closed and using IPLT (finger to finger or shoulder to shoulder) or no contact, provided 4 trials of 30-s duration in each of 12 posture-touch combinations. Sway (SD of the rate of change of upper trunk position at C7) was reliably less with IPLT compared with no contact, with two exceptions: in normal stance, shoulder contact with a partner in tandem stance, and in tandem Romberg stance, finger contact with a partner in the same stance, increased sway. Otherwise, the reduction in sway was greater with shoulder than with finger contact. Measures of interpersonal synchronization based on cross-correlations and coherence analysis between the partners’ C7 movements suggest different control factors operate to reduce sway in IPLT with the hand or shoulder contact.

interpersonal postural coordination; body sway

FINGERTIP LIGHT CONTACT with a static environmental reference point produces significant reduction in the variability of postural sway despite the provision of only minimal mechanical support (Holden et al. 1994). This has been demonstrated in young and older adults (Jeka and Lackner 1994; Tremblay et al. 2004) as well as in patient groups with sensory impaired balance (Dickstein et al. 2001; Jeka et al. 1996; Lackner et al. 1999). Shear forces from the tactile contact, in combination with information about contact location, derived from the distal-to-proximal proprioceptive chain, are thought to provide cues to body sway (Rabin et al. 1999). In general, forces at the fingertip include both normal and tangential components. Depending on finger orientation, these may be identified with anterior-posterior (AP) or left-right (LR) sway and afford cues to which the central nervous system (CNS) responds with adjustments to reduce the sway in each direction. Evidence that this is the basis for the light touch attenuation of body sway during upright standing includes small, but reliable, correlations between body sway and contact forces and torques. Cross-correlation time lags typically indicate a 250- to 300-ms lead of the tactile signal over subsequent postural adjustments (Clapp and Wing 1999; Jeka and Lackner 1994; Rabin et al. 2006).

The use of tactile feedback from light touch to reduce sway requires that the tactile sensory signal reflects own movement rather than that of the contact surface, and this may not necessarily be the case. For example, Jeka et al. (1997) showed that light finger contact with an oscillating reference increases postural sway, relative to the static contact, in synchrony with the movement of the reference. At higher frequencies of reference surface oscillation (>0.4 Hz), coherence with body sway decreases and phase lag increases (Jeka et al. 1997, 1998), suggesting that the feedback process, driven by both the velocity and position of the contact point, is limited by participants’ sensory motor lag introducing a low-pass filter effect. Moreover, removing the shear forces at the fingertip, by linking the movement of the contact point to body sway (sway-referenced light touch), increases sway, again indicating the importance of this form of tactile feedback in reducing body sway (Reginella et al. 1999).

A common form of light touch contact arises in a social context, when partners hold hands. We recently demonstrated that light fingertip-to-fingertip contact reduces postural sway in pairs of older adults (Johannsen et al. 2009). However, the reductions were less (13%) than those observed when light contact was kept with a static external reference (31%). The smaller reduction in sway during such interpersonal light touch (IPLT) may reflect the ambiguity of the tactile feedback signal regarding own body sway due to the partner’s sway. We were therefore interested in testing the effect of differing degrees of partner sway on own body sway during IPLT. In the present study we sought to assess the effect of each individual’s stance (normal bipedal vs. tandem Romberg), the contact site (distal finger vs. proximal shoulder), and the similarity of joint posture in young adults. Because both individuals were always standing side by side, we expected that shoulder-to-shoulder contact would make precision control of body sway more critical in the LR direction to reduce the risk of mutual destabilization due to the lower number of postural degrees of freedom available compared with standing with finger contact. Thus we assumed greater sway reduction with shoulder than finger contact, particularly in the LR direction. We also expected that inter-
personal light touch would become more effective with an increasing own contribution to the sensed contact force signal, and we therefore predicted that the reduction in sway would be less when the partner was in tandem compared with bipedal stance.

METHODS

Participants

Sixteen healthy adult participants were tested in eight pairs. In six pairs (mean 32.7 yr, SD 11.9 yr; 6 females, 6 males; 2 same-sex pairs, 4 mixed-sex pairs), light touch involved skin-to-skin contact between the two individuals. In the remaining two pairs (mean 45.6 yr, SD 11.2 yr; 2 mixed-sex pairs), additional trials were run in which the contact forces and torques between the participants were recorded using a miniature load sensor. All participants were recruited as an opportunity sample from the students and staff of the local research institute. Although pairings were allocated at random determined by participants’ availability for testing, individuals in a pair were likely to know each other, but none of the pairs constituted a couple in an established relationship. Written informed consent was obtained from all participants, and the study was approved by the University of Birmingham Ethics Committee.

Apparatus

The data acquisition setup consisted of a 12-camera optoelectronic motion capture system (Qualisys Oqus, Gothenburg, Sweden), 2 separate force platforms (model 4060H; Bertec, Worthington, OH), and a miniature load sensor (F/T sensor Nano17, 6 degrees of freedom; ATI Industrial Automation, Apex, NC). Body movements at C7 were sampled at 200 Hz, whereas data from the force platforms and the miniature force transducer were sampled at 1,200 Hz. Each platform measured the six components of the ground reaction forces and moments to determine the AP and LR components of center of pressure. The force platforms and load sensor were connected through a single multiplexed analog-to-digital converter (ADC) to the motion capture system, which synchronized the beginning and end of data acquisition for each experimental trial. In those two pairs of participants where the contact forces and torques between the participants were recorded, the sensor was placed between the skin contact surfaces by attachment to the person on the left with double-sided adhesive tape. Two lightweight 15-mm tubular plastic rods with reflective markers were attached to the load sensor and allowed position and orientation tracking of the sensor in three-dimensional space for mapping the sensor’s local force readings onto the global (force plate and kinematic) reference frame. The total weight of the force sensor assembly was 18 g.

Procedure

Participants stood side by side, oriented in the same direction, with eyes closed and heads facing forward. The side on which the taller person was standing was randomized. Participants were instructed to stand as still as possible in a relaxed manner without speaking.

Body sway was recorded in 12 different interpersonal joint posture conditions made up of 3 experimental factors: 1) individual stance posture, 2) similarity of the interpersonal joint postures, and 3) form of IPLT contact. Individuals were tested in two stance postures. In normal bipedal stance, participants kept a narrow-base standing posture with an ~5-cm interheel gap. In tandem Romberg stance, participants placed the nondominant foot in front of the dominant, keeping a heel-to-toe gap of ~5 cm. Similarity of the interpersonal joint posture was varied by fully permuting the two stance postures between both individuals. Thus, four interpersonal joint postures were performed by a pair. For the statistical analysis of interpersonal coordination, the number of interpersonal joint postures was reduced to three by averaging the two different interpersonal joint postures for each pair.

Figure 1 illustrates the interpersonal light touch and stance conditions. In IPLT conditions, contact between individuals was established either between the index fingertips of one hand or between the arms at a contact point near the shoulder. In “finger contact,” the person on the left force platform extended the right arm at the elbow, while the person on the right extended the left arm. The elbow of the extended arm was kept in contact with the torso at wrist level while the other arm was brought across the stomach so that the other hand made contact with the crook of the extended arm. The person on the left kept their right hand in pronation to touch the finger of the person on the right from above, while the latter kept his or her hand in supination. During “shoulder contact,” arm postures were similar except that participants kept their hands apart and moved slightly closer together so that contact was established with the outer surface of the arm at the shoulder. Practice trials were performed to ensure that participants were experienced in keeping touch as light as possible without losing contact. During the practice trials, the experimenter served as partner with each participant to provide verbal feedback about the appropriate IPLT force level and to demonstrate the required standing postures. Quantitative feedback about touch force was not given to participants. Finally, as a control condition, participants’ performance was also tested during “no contact,” when body posture was exactly the same as in the other two conditions except without physical contact between the participants.

Four trials (30 s each) were recorded for each of the 12 interpersonal joint postural conditions, resulting in a total of 48 trials for each pair of participants. The three interpersonal contact conditions were tested in blocks of 16 trials. The sequence of these blocks was ordered randomly. Within each block, four miniblocks of four trials each occurred in random order for each interpersonal joint posture.

Data Reduction and Statistical Analysis

All time series data were low-pass filtered at 10 Hz and differentiated to yield rate-of-change measures of sway (dc7, dCoP). Data analysis focused on sway, SD dc7 (with SD dCoP, which yielded similar findings; see Supplemental Material). (Supplemental data for this article is available online at the Journal of Neurophysiology website.)

The proportional change in SD dc7 sway during each of the eight IPLT conditions was calculated relative to the corresponding normal bipedal and tandem Romberg baselines without IPLT contact. On each axis, within-trial estimates of proportional sway change were averaged for every participant across trials for each experimental condition and subjected to repeated-measures ANOVA with stance posture, IPLT condition, and interpersonal joint postural similarity as within-subject factors. Significance levels were set at P = 0.05 after Greenhouse-Geisser correction.

Cross-correlation functions were calculated for two specific purposes. First, we aimed to analyze postural coordination between paired individuals for dc7 fluctuations in the AP and LR directions. Second, we used the data from the two pairs of participants, where a miniature load sensor recorded the components of contact forces, for cross-correlating each individual’s dc7 fluctuations with the force fluctuations in both horizontal directions. Cross-correlation functions were computed for lags ranging from +1,000 ms (shorter person leads; contact force leads dc7) to −1,000 ms (taller person leads; dc7 leads contact force). The largest absolute cross-correlation and corresponding time lag were extracted and were averaged for each experimental condition. All cross-correlation coefficients were Fisher Z-transformed (Fisher 1915) before statistical analysis was carried out. The between-individual cross-correlation coefficients were subjected to repeated-measures ANOVA with touch and interpersonal joint
posture conditions as within-subject factors, whereas the sway contact force cross-correlation coefficients were tested with stance posture, IPLT condition, and similarity of interpersonal joint posture as within-subject factors.

To extend the time domain analysis of interpersonal synchronization during IPLT, we estimated the magnitude squared coherence and the cross-power spectral density using Welch’s method (1967) on the C7-position time series. Our primary aim was to gain information on the sway frequency range at which the relation between the two individuals in a pair was strongest. For this the frequency spectrum was segmented into bins of 0.0244-Hz step size. Frequency bins from 0 to 0.1 Hz were excluded from the subsequent frequency peak extraction algorithm to avoid the inclusion of very slow drift effects commonly observed in quiet normal bipedal standing. Therefore, the frequency range considered extended from 0.1 to 10 Hz. The frequency bin with the peak magnitude coherence was found, and the corresponding relative phase angle was extracted from the cross-power spectral density distribution for every single trial. The peak magnitude coherence estimates were Fisher Z-transformed and subjected to repeated-measures ANOVA for each direction of sway with touch and interpersonal joint posture conditions as within-subject factors. The peak coherence frequency bins and corresponding relative phase estimates were analyzed similarly apart from the Fisher Z transformation. All data processing and analysis were performed in Matlab 7.5 (The MathWorks, Natick, MA) and SPSS 16 (IBM, Somers, NY). In this article, we only report those main effects and interactions that were at least marginally significant. Nonsignificant effects and interactions are not mentioned.

RESULTS

Contact Forces

The force transducer recordings in two pairs of participants indicated that the average normal force during finger contact was lower (both normal stance: mean 0.47 N, SD 0.21 N; both tandem stance: mean 0.55 N, SD 0.27 N; different stances:...
mean 0.54 N, SD 0.25 N) compared with shoulder contact (both normal stance: mean 0.78 N, SD 0.18 N; both tandem stance: mean 0.89 N, SD 0.31 N; different stances: mean 1.01 N, SD 0.39 N). The same was true for peak normal force during finger contact (both normal stance: mean 1.07 N, SD 0.21 N; both tandem stance: mean 1.25 N, SD 0.27 N; different stances: mean 1.21 N, SD 0.31 N) and shoulder contact (both normal stance: mean 2.01 N, SD 0.57 N; both tandem stance: mean 3.17 N, SD 0.27 N; different stances: mean 2.69 N, SD 0.57 N). Finally, the standard deviation of contact force across a trial was much lower during finger contact (both normal stance: mean 0.19 N, SD 0.003 N; both tandem stance: mean 0.20 N, SD 0.01 N; different stances: mean 0.20 N, SD 0.01 N) than during shoulder contact, where an increase in the force variability over the stability of joint stance postures was apparent (both normal stance: mean 0.33 N, SD 0.14 N; both tandem stance: mean 0.59 N, SD 0.07 N; different stances: mean 0.48 N, SD 0.12 N). Supplemental Fig. S1 shows two examples of the contact force fluctuations recorded between two paired individuals in different stances during finger and shoulder contact, respectively.

**Postural Sway**

Figure 2 shows illustrative dC7 fluctuations in two participants in different interpersonal joint postures during a single trial for each touch condition. The overall average dC7 values for no contact, finger light touch, and shoulder light touch conditions were 9.5, 8.0, and 7.0 mm/s, respectively. AP sway was greater than LR sway in normal stance (6.0 vs. 4.5 mm/s) and less in tandem stance (8.0 vs. 12.0 mm/s). The effects of contact conditions and joint posture interacted differently according to sway direction. In the following we present the results in terms of change relative to the no contact condition separately for each direction. The statistical analysis of body sway variability in terms of SD dC7 included data from all 12 participants where the miniature force transducer was not used. The pairwise temporal coordination between two participants was therefore analyzed in six pairs.

Figure 3 shows proportional sway change relative to the no contact baseline averaged across all individual participants as a function of the touch condition and the similarity of interpersonal joint posture for each stance. Negative values indicate a
reduction in sway, whereas positive values indicate an increase. In the AP direction, proportional sway change differed significantly between the two similarity conditions [F(1,10) = 7.22, P = 0.02, partial η² = 0.42]. When partners kept different stance postures, greater reductions in sway were observed for each of the two individuals in a pair than when both partners kept a similar stance. None of the remaining main effects or interactions reached statistical significance except for the interaction between stance posture and touch condition [F(1,10) = 5.27, P = 0.05, partial η² = 0.35]. Post hoc comparisons showed that in tandem Romberg stance, shoulder IPTL tended to cause greater proportional sway reductions than finger IPTL, while no difference between the IPTL conditions was apparent for normal bipedal stance. On the LR axis, a main effect of stance posture [F(1,10) = 5.49, P = 0.04, partial η² = 0.35] was observed. Tandem stance showed greater reductions than normal stance. Furthermore, the interaction between stance posture and touch condition was significant [F(1,10) = 41.49, P < 0.001, partial η² = 0.81]. Finally, there was a tendency for an interaction between stance posture and similarity of interpersonal joint posture [F(1,10) = 3.64, P = 0.09, partial η² = 0.27]. Post hoc comparisons showed that in tandem Romberg stance, shoulder IPTL induced greater proportional sway reductions than finger IPTL, which actually caused a slight increase when both partners were tandem Romberg. In normal stance, however, shoulder IPTL caused an increase in sway for individuals. Finally, a different interpersonal joint posture tended to be more beneficial in terms of proportional sway reductions for the person in tandem Romberg stance, whereas it tended to lead to greater proportional sway in normal stance.

Interpersonal Postural Coordination

Time domain. Across all three joint posture conditions, absolute peak cross-correlation coefficients indicating spatiotemporal coordination of postural adjustments in terms of dC⁷ between two paired individuals for the no contact control condition averaged 0.19 (SD 0.03) on the AP axis and −0.20 (SD 0.04) on the LR axis. In the finger contact condition, the average absolute peak cross-correlation coefficient was 0.22 (SD 0.03) on the AP axis and 0.22 (SD 0.02) on the LR axis. Finally, in the shoulder contact condition, the average cross-correlation coefficient was 0.26 (SD 0.03) on the AP axis and 0.51 (SD 0.04) on the LR axis.

In the AP direction, the cross-correlation coefficients differed as a function of touch condition [F(2,10) = 28.27, P < 0.001, partial η² = 0.85] and similarity of interpersonal joint posture [F(2,10) = 20.43, P = 0.005, partial η² = 0.80]. A significant interaction was found between touch condition and similarity of interpersonal joint posture [F(4,20) = 5.73, P = 0.01, partial η² = 0.53]. Post hoc comparisons demonstrated that in both finger and shoulder IPTL, significantly higher interpersonal synchronization occurred compared with no contact. Also, coefficients were generally higher when both partners were in normal bipedal stance. When both participants were standing in normal bipedal stance with both finger and shoulder contact, cross-correlation coefficients exceeded the highest absolute boundary of the 95% confidence interval of any no contact condition. In the LR direction, the cross-correlation coefficients differed as a function of touch condition [F(2,10) = 112.58, P < 0.001, partial η² = 0.96]. An interaction between touch condition and similarity of interpersonal joint posture was also present [F(4,20) = 5.93, P = 0.02, partial η² = 0.54]. Post hoc comparisons showed again that in shoulder contact, cross-correlation coefficients were greater compared with no contact. Furthermore, during shoulder contact coefficients were higher when both partners kept a different stance compared with both partners in tandem Romberg stance. All shoulder contact conditions exceeded the highest absolute boundary of the 95% confidence interval of any no contact condition. This means that only shoulder contact resulted in increased synchronization in the LR direction irrespective of the specific condition of interpersonal joint postural similarity. Cross-correlation coefficients as a function of touch
condition, similarity of interpersonal joint posture, and sway direction are shown in Fig. 4.

In the AP direction, the corresponding time lags of the peak cross-correlations that surpassed the critical threshold were 26 ms (SD 305; taller participant leads) for finger contact with both partners in the same stance, 283 ms (SD 215; taller participant leads) for both partners in normal bipedal shoulder contact, and 119 ms (SD 237; taller participant leads) for shoulder contact with both partners in different stances. Single comparisons against zero showed that the lead of the taller participant in normal bipedal shoulder contact was significant \(r(5) = -3.22, P = 0.02\). In the LR direction, time lags for peak cross-correlations surpassing the critical threshold during shoulder contact were 33 ms (SD 351; taller participant leads) for both partners in bipedal shoulder contact, 7 ms (SD 71; shorter participant leads) for both partners in the same stance, 283 ms (SD 215; taller participant leads) for finger contact with both partners in normal bipedal stance, 7 ms (SD 71; shorter participant leads) for both partners in different stances, and 66 ms (SD 219; taller participant leads) for both partners in tandem Romberg stance. No main effects or interactions as a function of touch condition or similarity of interpersonal joint posture were found for any of the two sway directions. None of these LR time lags were significantly different from zero lag.

**Frequency domain.** In the AP direction, magnitude squared coherence differed with touch condition \(F(2,10) = 7.80, P = 0.01, \text{partial } \eta^2 = 0.61\) and similarity of interpersonal joint posture \(F(2,10) = 4.21, P = 0.05, \text{partial } \eta^2 = 0.46\). Post hoc comparisons showed that coherence was significantly higher during shoulder contact (mean 0.32, SD 0.02) compared with no contact (mean 0.27, SD 0.03; \(F(1,5) = 17.97, P = 0.008, \text{partial } \eta^2 = 0.78\)) and tended to be higher compared with finger contact (mean 0.29, SD 0.04; \(F(1,5) = 4.49, P = 0.09, \text{partial } \eta^2 = 0.47\)). Also, both partners in normal bipedal stance resulted in higher average coherence than both partners in tandem stance. Similar to peak cross-correlations, shoulder contact with both partners in normal bipedal stance exceeded the highest absolute boundary of the 95% confidence interval of any no contact condition. In the LR direction, peak coherence differed only as a function of touch condition \(F(2,10) = 25.31, P = 0.002, \text{partial } \eta^2 = 0.84\). Post hoc comparisons indicated that shoulder contact (mean 0.50, SD 0.09) resulted in higher coherence than both finger contact and no contact [finger contact: mean 0.29, SD 0.03; no contact: mean 0.27, SD 0.02; both \(F(1,5) > 21.78, P < 0.002, \text{both partial } \eta^2 > 0.81\)]. During shoulder contact, all three interpersonal joint postures exceeded the highest absolute boundary of the 95% confidence interval of any no contact condition.

Interpersonal relative phase did not differ between experimental conditions in either the AP (mean 1.05 deg, SD 10.87 deg) or the LR direction (mean 2.23 deg, SD 24.51 deg). On the other hand, the variability of interpersonal relative phase was not the same across the touch conditions in both directions of sway [AP: \(F(2,8) = 5.80, P = 0.05, \text{partial } \eta^2 = 0.59\); LR: \(F(2,8) = 28.23, P = 0.005, \text{partial } \eta^2 = 0.88\)]. Post hoc comparisons showed that the variability of interpersonal relative phase during shoulder contact (AP: mean 66.00 deg, SD 18.88 deg; LR: mean 31.85 deg, SD 21.99 deg) was significantly lower than during finger contact (AP: mean 97.52 deg, SD 12.04 deg; LR: mean 85.13 deg, SD 13.34 deg) or no contact (AP: mean 90.39 deg, SD 16.72 deg; LR: mean 105.04 deg, SD 33.95 deg).

The average peak coherence frequency as a function of touch condition and sway direction is shown in Fig. 5. Overall peak coherence frequency was at 2.94 Hz (SD 0.40 Hz) in the AP direction. No main effects or interaction between touch conditions and similarity of interpersonal joint posture were found. In contrast, in the LR direction, peak coherence frequency was different between the touch conditions \(F(2,10) = 8.74, P = 0.02, \text{partial } \eta^2 = 0.64\). Post hoc comparisons indicated a significant shift in the peak coherence frequency in shoulder contact to a lower frequency band compared with finger contact and no contact.

**Relationship Between Contact Force and Sway**

For our analysis of the relationship between fluctuations of dC7 and the horizontal contact force components, we utilized the absolute peak cross-correlation coefficient and its corre-

![Fig. 4. Peak absolute cross-correlation coefficients between 2 individuals of a pair for dC7 as a function of interpersonal light touch condition and interpersonal postural similarity. A: cross-correlation coefficients for dC7 in the AP direction. B: cross-correlation coefficients for dC7 in the LR direction. Error bars indicate SE. *P < 0.05 indicates a significant single comparison. The dashed lines indicate the upper and lower boundary derived from the absolute maximum 95% confidence interval for any of the 3 no contact conditions. Abs max xcorr, absolute maximum cross-correlation.](http://jn.physiology.org/doi/abs/10.1152/jn.00149.2011)
On the AP axis, only the effect of touch was significant \( F(1,3) = 44.89, P = 0.007, \text{partial } \eta^2 = 0.94 \) due to shoulder contact leading to stronger cross-correlations than finger contact. In the LR direction, coefficients showed main effects of touch condition \( F(1,3) = 16.37, P = 0.03, \text{partial } \eta^2 = 0.85 \) and stance posture \( F(1,3) = 24.31, P = 0.02, \text{partial } \eta^2 = 0.89 \) as well as an interaction between touch condition, stance posture, and similarity of interpersonal joint posture \( F(1,3) = 27.50, P = 0.01, \text{partial } \eta^2 = 0.90 \). Tandem Romberg stance resulted in higher coefficients than normal bipedal stance, and shoulder contact resulted in higher coefficients than finger contact. Post hoc comparisons explained the three-way interaction with an increase in the cross-correlation coefficients when in normal bipedal stance with shoulder contact to a partner in tandem Romberg compared with contact with a partner in the same normal bipedal stance.

No main effects or interactions were found for the cross-correlation time lags on either axis. Overall averages expressed a lead of the force signal by 71 ms (SD 171 ms) on the AP axis and a lead by the person by 343 ms (SD 304 ms) on the LR axis. Both measures, however, were not significantly different from zero lag.

**DISCUSSION**

In quiet standing, the variability of sway is reduced by light touch contact with a static environmental referent (Holden et al. 1994; Jeka and Lackner 1994). The reduction in sway is generally assumed to reflect the use of tactile feedback from the contact. If the contact surface moves, sway increases, as if no allowance were made for its movement (Jeka et al. 1997; Wing et al. 2011). Light touch contact with a moving surface
commonly occurs in a social context in hand holding. In the present study we examined how IPLT effects on sway may depend on contact location and on the stance of young adults. We predicted alterations in the extent to which an individual would utilize the force signal for the fine-tuning of postural adjustments, and this would depend on the variability of the signal as well as the demands for precise direction-specific modulation of sway. Thus we expected that sway would be reduced less if the partner stood in tandem stance, compared with a partner in bipedal stance, due to the generally increased variability of the touch signal from the partner. This should apply especially to situations in which both individuals adopted differing stance postures (asymmetrical interpersonal stance posture: one person in normal bipedal, one in tandem Romberg). Our expectation for this situation was that the more stable individual would contribute less to the variability of the touch signal and therefore would receive less specific feedback about own body sway and, as a consequence, would show smaller sway reductions. Finally, given the requirement of precision control of body sway, we assumed that shoulder-to-shoulder contact would force participants to constrain their sway actively to compensate for the lower number of postural degrees of freedom of this more proximal contact.

We found that IPLT reduced sway of an individual in both normal bipedal and tandem Romberg stance. The proportional reduction of sway during finger contact (9–15%) was comparable to the figure we obtained for older participants using three-finger IPLT (Johannsen et al. 2009). However, in the present study, differences between finger and shoulder contact were apparent depending on stance posture. In normal bipedal stance, sway was reduced mainly during finger contact for both directions of sway. In the LR direction, shoulder-to-shoulder contact even increased sway. Interestingly, these particular conditions were the ones in which an individual in tandem Romberg showed the greatest reductions in sway during IPLT. A slight increase in sway, however, was observed in the AP direction when both partners were standing in tandem Romberg and were keeping finger contact.

The above alterations in sway may be invoked by a force feedback control loop where the sway-related contribution to the afferent touch signal facilitates more efficient subsequent postural adjustments through improved perception of own sway (Jeka and Lackner 1994). For example, during light touch with an inanimate, earth-fixed reference point, the force signal variability can be attributed exclusively to own sway. During IPLT with a partner in the same stance posture, each partner may contribute equally to the signal, whereas in an asymmetrical joint posture, the individual in the less stable stance might cause the greater amount of variability. According to this notion, a higher contact point, such as during shoulder contact, would result in greater proportional sway reductions due to an increase in sway-related shear forces (Krishnamoorthy et al. 2002; Rogers et al. 2001), yielding a more direct indication of body sway. Further support for this hypothesis comes from stronger cross-correlations between contact force components and sway, especially in the LR direction, irrespective of finger or shoulder contact in tandem Romberg stance. Overall, in tandem Romberg stance, sway reduced progressively with light touch contact with another individual, with a more proximal contact point at the shoulder and with a larger own contribution to the force signal relative to a more stable partner. In contrast, in finger contact, the additional shoulder and elbow degrees of freedom decouple the linkage with body sway.

We believe, however, that the force feedback hypothesis only partly explains the mechanisms at work during IPLT. In addition to the force feedback, with shoulder contact individuals may have chosen a control strategy that involves a greater degree of constraint on active sway to keep touch light (Riley et al. 1999). The requirements for such a strategy would be less during finger IPLT, because intrinsic touch precision would presumably be greater due to additional limb movement degrees of freedom (Rabinet al. 2008). Similar to the hypothesis of constraints on active sway, feed-forward reductions in sway have been suggested to result from a “suprapostural” task goal such as keeping the contact force below a specified threshold, for example, below 1 N (Riley et al. 1999). In this regard, one might speculate whether minimization of the contact force could have become an implicit suprapostural task goal that affords proactive sway control. Besides keeping the contact force light, however, partners may also have tried to minimize the variation of the contact point in spatial coordinates to facilitate interpersonal coordination. In situations where postural control served precise performance in a secondary task such as visual gaze fixation or manual aiming, direction-specific minimization of sway at the cost of increased sway in the perpendicular direction has been demonstrated (Balasubramaniam et al. 2000; Mitra 2004; Stoffregen et al. 1999). On the other hand, we did not find any indications for a similar effect during IPLT; that is, reduced sway on the LR axis at the cost of sway increases in the AP direction. This observation may indicate that during IPLT, the precision demands are qualitatively different from gaze fixation or manual aiming. For example, the specific contact point location might not have been represented in an allocentric spatial reference frame. It appears more likely that the contact point was located in an egocentric frame of reference given that the notion of a change from an allocentric to an egocentric trunk-based reference frame during individual light touch has been proposed in a recent publication by Franzen et al. (2011).

Fingertip light touch increases interpersonal synchronization of postural adjustments during rhythmic externally paced voluntary sway at a low (0.24 Hz) frequency (Sofianidis et al. in press) as well as during quiet standing (Johannsen et al. 2009). In quiet standing, increased positive cross-correlations indicated sway in the same direction with near-zero phase lag in contrast to two control conditions without IPLT where cross-correlations were not significant. One possibility to interpret this zero phase lag would be mutual light touch entrainment, similar to keeping contact with an oscillating reference (Jeka et al. 1997). On the other hand, fingertip exposure to a periodic haptic driving stimulus that replicates a natural sway pattern increases postural sway compared with a control condition without contact (Wing et al. 2011). We conclude from that particular observation that IPLT is more than a process of mutual sway entrainment.

In the present study, we also found evidence for increased interpersonal postural coordination, although it was modulated by the sway direction, the interpersonal stance symmetry, and the site of IPLT. For AP sway, interpersonal coordination appeared to be present only in symmetrical normal bipedal stance for both finger and shoulder contact, whereas for LR sway, increased interpersonal coordination was present during...
shoulder contact only irrespective of the stance and the interpersonal stance symmetry. The more proximal contact site at the shoulder gave rise to stronger interpersonal coordination, possibly due to a more direct transmission of the trunk’s sway or a more fixed alignment with fewer postural degrees of freedom. A coherence analysis confirmed the findings in the time domain but provided additional insight as well. Although the frequency of the peak coherence was not different between touch conditions in the AP direction, with an average frequency bin at ~3 Hz, shoulder contact almost halved peak coherence frequency on the LR axis. In addition, the variability of relative phase was also lower during shoulder contact. This longer oscillatory period may indicate a qualitative change in the nature of interpersonal coordination during shoulder contact. Whereas a period of 300 ms during finger contact but also no contact may express commonalities between individuals with respect to “natural” sensory feedback-driven adjustments of sway, a period of 600 ms in duration may be caused by a postural strategy that facilitates tracking of each other’s sway movements. For example, task-specific combinations of postural control synergies including situations with light touch contact have been reported previously (Krishnamoorthy et al. 2004). During visually guided LR weight shifting, the control synergy is shifted from the hip to the ankle muscles to achieve the precision requirements of the task (Hatzitaki and Konstadakis 2007). An ankle strategy may therefore dominate shoulder-to-shoulder contact as suggested by the reduction in the primary peak coherence frequency.

This study confirmed the zero lags for the conditions with significant cross-correlations between individuals except for a lead of the taller individual with respect to AP sway with shoulder contact and both partners in normal bipedal stance. This observation, however, contrasts with the shorter interindividual lags on the LR axis in the same stance situation and may indicate a functional dissociation between both sway directions in terms of the interpersonal coordination. A mechanical support strategy between both individuals may be considered as a possible explanation for the observed increases in the contact force levels and the relatively short time lags during shoulder contact. This “tripod strategy” achieved by leaning and oscillating toward the partner in an anti-phase coordination pattern should result in negative interpersonal cross-correlations, which we did not observe. Although we recognize that short-term mechanical effects, i.e., mutual perturbations, may increase apparent interpersonal coordination, we do not believe that individuals in a pair chose a mechanical support strategy. Had they done so, force levels would be expected to be higher and within-trial force variability lower during shoulder than finger contact. In addition, we would expect much higher interpersonal cross-correlations than the ones actually found. In our opinion, a mechanical support strategy would have been most likely during shoulder contact, when both partners were in tandem Romberg stance. In contrast, we observed increasing force levels with increasing within-trial standard deviation of contact force, which indicates that keeping shoulder contact becomes more demanding with less stable joint stance postures. We suggest that both participants’ sway may also have been influenced by the shared perception of the contact point’s directional motion. A spatial tracking mechanism would enable prediction of the contact point position, and thus more precise control of the contact forces, because the difference in acceleration between both individuals would be minimized. In addition, participants may have extracted their partners’ movements from the variability of the force signal and the position change that could not be accounted for by an internal source such as own body sway.

It is remarkable that on the LR axis, a dissociation between reduction of sway and interpersonal in-phase coordination seems present for finger IPLT (significant reductions in sway without interpersonal coordination) in contrast to shoulder IPLT, where both effects appear to be associated. We suggest, therefore, that in the case of finger IPLT, where an additional rotational degree of freedom is available on the LR axis, feedback from the fingertip might be used to drive movements of the upper limb for minimizing contact force directly. If the contact force and thus the touch feedback is minimized, however, it appears contradictory that the remaining signal would still be sufficient to inform about own body sway and result in improved postural adjustments. In this case, feed-forward postural adjustments related to such upper limb movements (Bouisset and Zattara 1987) might be the basis for the link between IPLT and reduction in sway. Thus employing the upper limb’s extra movement degree of freedom in finger IPLT may reduce the coupling between touch feedback and subsequent postural adjustments and also the coordination between both partners.

In conclusion, the present study investigated in young adults the effect of light touch contact between two individuals on each individual’s control of body sway as a function of the skin contact site, each individual’s stance posture, and the interpersonal stance symmetry. Reliable reductions in sway were found during both forms of IPLT. Distal IPLT at the fingertip, however, differed from more proximal IPLT at the shoulder with respect to the proportional reduction in sway depending on an individual’s and the partner’s stance posture. In-phase interpersonal postural coordination with near-zero lag became evident during shoulder-to-shoulder contact on the LR axis. We propose two different mechanisms for maintaining IPLT during shoulder and finger contact.

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AUTHOR CONTRIBUTIONS

L.J., A.M.W., and V.H. conception and design of research; L.J. performed experiments; L.J. analyzed data; L.J., A.M.W., and V.H. interpreted results of experiments; L.J. prepared figures; L.J. drafted manuscript; L.J., A.M.W., and V.H. edited and revised manuscript; L.J., A.M.W., and V.H. approved final version of manuscript.

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