Effects of Maintaining Touch Contact on Predictive and Reactive Balance

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Johannsen L, Wing AM, Hatzitaki V. Effects of maintaining touch contact on predictive and reactive balance. J Neurophysiol 97: 2686–2695, 2007. First published February 15, 2007; doi:10.1152/jn.00038.2007. Light touch contact between the body and an environmental referent reduces fluctuations of center of pressure (CoP) in quiet standing although the contact forces are insufficient to provide significant forces to stabilize standing balance. Maintenance of upright standing posture (with light touch contact) may include both predictive and reactive components. Recently Dickstein et al. (2003) demonstrated that reaction to temporally unpredictable displacement of the support surface was affected by light touch raising the question whether light touch effects also occur with predictable disturbance to balance. We examined the effects of shoulder light touch on SD of CoP rate (dCoP) during balance perturbations associated with forward sway induced by pulling on (voluntary), or being pulled by (reactive), a hand-held horizontal load. Prior to perturbation, SD dCoP was lower with light touch, corresponding to previous findings. Immediately after perturbation, SD dCoP was greater with light touch in the case of voluntary pull, whereas no difference was found for reflex pull. However, in the following time course, light touch contact again resulted in a significantly lower SD dCoP and faster stabilization of SD dCoP. We conclude that shoulder light touch contact affects immediate postural responses to voluntary pull but also stabilization after voluntary and reflex perturbation. We suggest that in voluntary perturbation CoP fluctuations are differentially modulated in anterioposterior and mediolateral directions to maintain light touch, which not only provides augmented sensory feedback about body self-motion, but may act as a “constraint” to the postural control system when preparing postural adjustments.

INTRODUCTION

The maintenance of standing balance involves a mixture of reactive and predictive control processes (Massion 1992, 1994). Sensory cues from unexpected imposed forces or torques producing disturbances in the position of the center of mass (CoM) relative to the base of support (BoS) result in multisegmental postural adjustments. These stiffen the musculoskeletal structure allowing ground reaction forces to oppose the applied forces and torques (Balasubramanian and Wing 2002; Nashner and McCollum 1985) and tend to restore CoM over BoS. The amplitude of the postural response scales with the applied force and the onset latency is typically 70–100 ms, which is sufficient for supraspinal, possibly cortical, pathways (Diener et al. 1988).

Predictable disturbances to balance caused by voluntary movement, such as raising of the arms (Bouisset and Zattara 1987; Cordo and Nashner 1982) or forward displacement of a mass (Wing et al. 1997), are associated with anticipatory postural adjustments. These result in ground reaction forces that can lead the focal movement by ≥100 ms and serve to reduce the impact of the voluntary movement on standing posture (Benvenuti et al. 1997; Bouisset and Zattara 1987). Setting of these adjustments may involve an internal forward model that predicts the consequences of the focal movement (Massion 1994). Alternatively, anticipatory postural adjustments may be based on an inverse model, which could be trained by feedback error learning (Kawato and Wolpert 1998).

Quiet standing involves a series of minor postural adjustments that result in fluctuations of the center of pressure (CoP). The discrepancy between the CoP and the vertical projection of the CoM is proportional to the acceleration tending to restore the CoM to a position centered over the BoS (Winter et al. 1996). The resulting changes in body position are termed body sway (Nashner 1971). Sway increases when sensory inputs (e.g., vision) are reduced or degraded, and this indicates the importance of feedback in limiting sway. Normal feedback routes can be augmented in several ways. For instance, auditory or vibratory signals that are directionally linked to postural sway result in reduced CoP fluctuations (Chiari et al. 2005; Dozza et al. 2005a,b; Wall et al. 2001). Light touch (LT), in which one digit rests gently (for example, 1 N contact force) against a stable environmental referent, also reduces postural sway in quiet standing (Clapp and Wing 1999; Jeka and Lackner 1994). Sensory augmentation by light touch can be very effective, for instance, completely suppressing the increased sway associated with leg muscle vibration during quiet standing (Lackner et al. 2000). Light touch is more effective when fingertip contact is maintained in the plane of greater sway (more unstable direction) (Rabin et al. 1999). Light touch contact when the finger is held in position by an external clip is even more effective in reducing sway than free finger contact (Krishnamoorthy et al. 2002; Rogers et al. 2001).

One possible reason that light touch reduces sway is that it provides a time-advanced cue to sway. This view receives support from the finding of a correlation between contact force and CoP with finger contact force leading CoP by 250–300 ms in mediolateral (ML) (Jeka and Lackner 1994, 1995; Rabin et al. 1999) and anterioposterior (AP) (Clapp and Wing 1999; Rabin et al. 1999) directions. Thus according to a feedback control account, a change of the fingertip forces occurs before the EMG response; this shows a 150-ms lead over CoP, which in turn leads sway by 150 ms (Barela et al. 1999; Jeka and Lackner 1995; Rabin et al. 1999). Recently it was shown (Rabin et al. 2006) that light touch effects develop rapidly in quiet standing over the first 2–3 s of contact with a downward
trend in the absolute error of the CoP detectable in the initial 200 ms. In this study, the correlation between finger tip shear force and CoP was at a maximum when CoP lagged shear force by 320 ms.

Light touch contact need not be restricted to the finger but also works when applied to other body segments. For example, light touch contact with shoulder and leg has been shown to be effective in reducing postural sway (Rogers et al. 2001). Light touch to the head or neck can be more effective in reducing body sway than light touch at the finger tip (Krishnamoorthy et al. 2002). These and other findings suggest that, to reduce sway, the postural system makes use of two types of sensory information from light touch contact: one related to the provision of a fixed reference point in space (Reginella et al. 1999), the other related to the information provided by transient forces developed between the body part and the contact surface (Krishnamoorthy et al. 2002; Rogers et al. 2001).

The majority of studies reporting reduction of postural sway with light touch used a paradigm in which participants kept a static, upright standing posture. It is unclear what are the relative contributions of predictive and reactive elements in the control of balance in this situation. It would be interesting to know whether light touch contributes equally to both aspects of control. Another question is whether light touch is effective for transient disturbances to balance, that is, the dynamic aspects of postural control. A recent study sought to determine whether light touch results in facilitation of postural reflexes triggered by transient balance perturbations (Dickstein et al. 2003). In this study, light touch during quiet standing was combined with sudden 6 cm backward translation of BoS at one of three different velocities. Although no reliable effects of light touch were observed on the latency of postural reflexes after the perturbation, their gain, as indexed by CoP rate relative to BoS velocity, increased with light touch. Moreover, it was noted that light touch tended to act as a “constraint” on postural adjustments in that the latter evidenced AP and ML components that served to maintain light touch contact. Thus with light touch, the rate of the (forward) CoPAP response was reduced and the rate of the (rightward) CoPML response increased, these changes in COP components being compatible with increased trunk movement toward the location providing light touch contact. Given the increase in gain of the postural reflex with light touch, it is interesting to ask whether, after perturbation, postural sway and CoP fluctuations were reduced; however, this study did not evaluate this (Dickstein et al. 2003).

In the present study, we examined light touch effects on CoP fluctuations both during and after reflex postural response to sudden-onset perturbations to balance. In addition, we compared the effect of light touch on postural reflexes with its effect on anticipatory postural adjustments associated with voluntary perturbations to balance. The two contrasting dynamic contexts involved a voluntary, self-imposed balance perturbation (pulling on a manipulandum with the right hand; hence anticipatory) compared with an externally imposed perturbation of balance (being pulled by the manipulandum; hence reactive). To reduce the situational demands and avoid potential bimanual conflict if light touch had required use of the other hand, light touch contact was applied to the left arm near the shoulder rather than to the left hand.

On the basis of the previous study showing light touch contact effects on the gain of the postural reflex in reactive balance (Dickstein et al. 2003), we expected light touch would enhance the postural response at the onset of the external perturbation. In contrast, given that anticipatory postural adjustments tend to minimize postural disturbance associated with voluntary movement (Bouisset and Zattara 1987), assuming these are already optimal, we hypothesized that light touch contact would cause no further improvements of the anticipatory postural adjustments. We did not therefore expect that light touch would have an effect on stabilization after perturbation associated with voluntary compared with reactive postural responses.

METHODS

Participants

Eleven right-handed adults served as participants [age: 30.1 ± 11.6 (SD) yr]. None reported any neurological or musculoskeletal disorders. All gave their informed consent, and the experiment had the approval of the local ethical committee on testing human participants.

Apparatus

Participants stood in stockinged feet on a force platform (4060H, Bertec) used to measure the six components of the ground reaction forces and torques to determine the AP and ML components of CoP fluctuations (see Fig. 1). Participants held a manipulandum (M) in precision grip (using the digit pads of the thumb and 1–3 fingers) with the right hand at waist height. The manipulandum comprised two one-dimensional (1D) force transducers (F250, Novatech Hastings) configured in orthogonal orientations to allow simultaneous recording of both the horizontal load force (load) acting on the manipulandum and the normal grip force (grip) exerted by the participant on the manipulandum. Two horizontal steel cables attached to the manipulandum and, over pulleys, to two counter weights kept the manipulandum at a constant position in space. An additional weight (15 N) could be added to one of the counter weights to produce a forward load acting on the manipulandum.

A second pair of two orthogonally mounted 1D force transducers (F250, Novatech Hastings) was mounted on a rigid horizontal support bar fixed to a vertical stand. These transducers were adjusted to apply light touch to the left arm of the participant near the shoulder through a flat wooden endplate covered with a layer of fine grit sandpaper, which provided a textured contact surface. The force transducers recorded normal and shear forces at the left arm aligned with ML and AP directions of the force platform.

Participants’ movement kinematics of the trunk and the right hand were registered using a six-camera optoelectronic motion tracking system (VICON 512, Oxford Metrics) with reflective markers attached to the neck (spinal bone C7), right shoulder, and right wrist. EMG activity was recorded over right lateral gastrocnemius (GAS), first dorsal interosseus of the right hand (1D1) and biceps (BIC), and triceps (TRI) of the right arm. The EMG signals were amplified (gain: 3,400) by means of battery-powered amplifiers near the electrodes and passed through a unity gain isolating amplifier.

Data from the force platform, force transducers and EMG electrodes were sampled at 1,080 Hz. Kinematics were sampled by the camera system at 120 Hz via a 16-bit analog interface (VICON datastation, Oxford Metrics).

Procedure

Participants were instructed to stand upright, with eyes closed, head facing forward, as still as possible with 12-cm ML separation of the
FIG. 1. Drawing of the experimental setup. The participant stood with eyes closed on a force plate. Precision grip (opposed thumb and fingers) was used to lightly grasp the manipulandum, which was attached through a pulley system to a basket behind the participant. Light touch to the left arm of the participant near the shoulder was applied through a flat wooden endplate covered with a layer of fine grit sandpaper, which provided a textured contact surface. In different blocks of trials, a weight was dropped into the basket, and the participant resisted the pull by holding on and steadying the manipulandum (reflex pull), or the participant pulled on the manipulandum to lift the basket and weight off the support (voluntary pull). Three reflective markers were attached to the participant to permit motion tracking of the neck C7, right shoulder, right wrist. Surface EMG was used to record muscle activity of 1st dorsal interosseus of the right hand, the biceps and triceps of the right arm and lateral gastrocnemius of the right leg.

inner border of their heels. A template was used to mark the positions of the feet on the platform so that this posture could be maintained throughout the experiment. They were instructed to hold the manipulandum under two contrasting horizontal loading conditions that were tested in separate blocks. During reflex pull, the manipulandum was subject to an added forward load caused by the weight (15 N) being released at an unpredictable time. The weight was released manually on each trial with slightly varying height which resulted in a variable maximum load (Loadmax) and load rate (dLoadmax). At the beginning of each trial, participants kept light contact with the manipulandum so that they could detect the sudden load onset. During voluntary pull, participants started the trial with fingers near but not in contact with the manipulandum. In their own time, they then gripped and pulled the manipulandum horizontally to quickly lift the 15 N weight off a support. During reflex pull as well as voluntary pull trials, participants were required to keep a steady hold on the manipulandum until the trial ended. These loading conditions were combined with two touch conditions involving either light touch or no touch at the left shoulder. In the light touch condition, participants were instructed to use the minimum force required to keep contact; no concurrent feedback was provided about the contact forces.

Twenty trials of 10-s duration were run in each of the four conditions (reflex pull/light touch, reflex pull/no touch, voluntary pull/light touch, voluntary pull/no touch). Each condition was tested in two blocks of 10 trials. The blocked sets of the four conditions were randomized but participants had to complete at least one block of 10 trials in each condition before the second block in the same condition was presented. During each trial the perturbation of standing balance by reflex pull or voluntary pull occurred between 3 and 7 s after trial onset. Prior to data collection in each trial, participants were instructed to close their eyes and to say when they were ready to commence the trial.

Analysis

ML and AP components of the kinematics and the kinetics were digitally low-pass filtered at 10 Hz (dual pass 4th-order Butterworth filter) and differentiated to obtain rate based measures (dLoad, dGrip, dNormal, dShear, dCoPAP, dCoPML) that afforded stable zero-valued baselines prior to perturbation. EMG recordings were band-stop filtered between 48 and 52 Hz and subsequently rectified to obtain the EMG envelope. Afterward, the EMG envelopes were also low-pass filtered at 10 Hz (dual pass 4th-order Butterworth filter).

Individual data streams were analyzed using custom interactive waveform measurement software written in Labview (7.1) and Matlab (7.0). Times of onset for dLoad and dGrip as well as onset of dCoPAP and dCoPML, and of EMG envelopes (GAS, 1DI, BIC, TRI) were determined using a cut-off threshold of 4 SD above baseline (before perturbation). Relative onset times for each variable were then computed by subtracting the dLoad onset time. After rejecting those relative onset times with an absolute value &gt; 5 s, the remaining relative onset times were analyzed using three-way repeated-measures ANOVA (SPSS 11.5) with muscle, loading condition, and touch as independent factors.

To investigate the time course of the balance response, each trial was segmented into periods of 1-s duration starting from 2 s before to 4 s after onset of dLoad and the within-trial mean (AV) and within-trial SD of dCoP in AP and ML directions were determined for each time segment. For the statistical analysis of AV and SD, the time course was subdivided into two phases: baseline before perturbation, preceding dLoad onset (t &lt; 0 s), and after perturbation following dLoad onset (t &gt; 0 s). The data for each phase were then subject to repeated-measures ANOVA with loading and touch conditions as the primary independent factors and direction and time (2 time intervals for 1st phase; 5 time intervals for 2nd phase) as additional factors. SD CoP data for the second (perturbation) phase were linearized by computing the natural logarithm (ln) before the statistical analysis.

To describe the stabilization of posture following the perturbation for each single trial, we determined the fit of an exponential decreasing function \[ x(t) = C + A e^{-\alpha t} \] to the reduction in SD of dCoPAP and dCoPML across the five 1-s time intervals after the perturbation. The three function parameters C (asymptote), A (intercept x0), and B (time constant) were determined using a least-squares estimation algorithm and were subsequently averaged for each experimental condition and each participant.

To characterize touch forces during light touch, touch force rates dShear and dNormal were analyzed at the left shoulder in terms of AV and SD using two-way repeated-measures ANOVA with time (2 time intervals for 1st phase; 5 time intervals for 2nd phase) and loading as independent factors.

RESULTS

In the following, we first present data relating to the efficacy of the experimental paradigm, then consider the effects of touch on maintenance of balance.

Effects of loading condition on pulling responses

The experimental conditions resulted in an overall average Loadmax of 26.5 ± 2.2 (SD) N for voluntary pull and 18.3 ± 0.7 N for reflex pull. Overall average dLoadmax was 178.9 ±
49.8 N/s for voluntary pull and 103.3 ± 10.1 N/s for reflex pull. The difference between loading conditions was reliable for both variables [both \( F(1,10) = 22.37, both \ P = 0.001 \)]. There was no difference in Load\(_{\text{max}}\) or dLoad\(_{\text{max}}\) as a function of Light touch contact.

Figure 2 shows illustrative data (gray traces) aligned on dLoad onset from three single trials as well as the average data (black line) for all 20 trials of a single participant performing a voluntary pull and a reflex pull, both with light touch contact. Figure 2A shows measures from the manipulandum and the right hand, whereas B shows measures relating to the postural response and right shoulder contact. Inspection of the traces reveals broadly similar responses in the two conditions (but note the lower dLoad\(_{\text{max}}\) and reversed sign of the wrist velocity in reflex pull). However, there is a marked contrast in timing with responses in voluntary pull occurring with or slightly before dLoad onset, whereas in reflex pull the responses clearly follow dLoad onset. The lowest two panels of Fig. 2B show considerable variation in the touch force at the right shoulder, both within and between trials. AV normal force over all participants in the two loading conditions was 2.9 ± 1.4 N with no significant difference between voluntary and reflex pull conditions. Also, the absolute AV shear force (mean = 0.8 ± 0.5 N) was not reliably different between the two loading conditions.

An analysis of the relative onset times for dGrip and dCoP\(_{\text{AP}}\) and for each of the four muscles supported the contrast in timing of the response between voluntary pull and reflex pull evident in Fig. 2. Onset of dGrip showed a significant effect of loading condition \( [F(1,10) = 329.22, \ P < 0.001] \) but no effect of touch and no interaction between loading and touch. During voluntary pull, dGrip onset preceded dLoad onset on average by 46 ± 38 ms while it was delayed on average by 157 ± 46 ms in reflex pull. Onset of dCoP\(_{\text{AP}}\) was also affected by loading \( [F(1,10) = 131.01, \ P < 0.001] \) and touch \( [F(1,10) = 8.43, \ P = 0.02] \), but there was no interaction. The average delay of dCoP\(_{\text{AP}}\) onset relative to dLoad onset was 9 ± 48 ms in light touch and 13 ± 56 ms in no touch in voluntary pull. Relative

**FIG. 2.** Illustrative data (gray traces) for each dependent measure from 3 trials of a single participant with light touch contact at the left shoulder during either voluntary (left) or reflex (right) pull. The thick black line represents the average of the same participant across all 20 trials in the 2 loading conditions. A: measures from the manipulandum (M) and the right hand: load force rate (dLoad), wrist anterioposterior (AP) velocity, grip force rate (dGrip), 1st dorsal interosseous and gastrocnemius lateralis electromyogram (EMG). At the manipulandum, an increased transducer voltage signified decrease in load and increase in grip. B: measures relating to the postural response and right shoulder contact: CoP velocity in both directions, C7 velocity in the AP direction, shear force, and normal force rates. In the AP direction, a positive sign signified forward directional shift of CoP, and leftward shift in the mediolateral (ML) direction (toward light touch contact surface at the left shoulder). For the contact forces, a positive sign indicated a forward directed shear force in the AP direction, while in the ML direction a positive sign indicated leftward increasing normal force. Each trace is aligned at time 0 with the onset of dLoad for that trial.
onset of dCoP<sub>AP</sub> in reflex pull was much later with an average latency of 264 ± 55 ms in light touch and 290 ± 49 ms in no touch.

Analysis of relative onset times of the EMG revealed a significant effect of loading \( [F(1,10) = 109.52, P < 0.001] \) and of muscle \( [F(3,30) = 11.36, P < 0.001] \) but no effect of touch and only an interaction between loading and muscle \( [F(3,30) = 5.36, P = 0.004] \). Both 1DI and TRI exhibited relative onset times that were similar to those for dGrip. Average 1DI onset times (VP: −58 ± 45 ms; RP: 153 ± 39 ms) slightly preceded the onset of dGrip, whereas average onset of TRI (VP: −32 ± 43 ms; RP: 198 ± 63 ms) occurred slightly later. The average onset of GAS (VP: 0 ± 83 ms; RP: 283 ± 130 ms) coincided closely with the onset of dCoP<sub>AP</sub>. The average onset of BIC was delayed by 131 ± 167 ms) during voluntary pull and by 296 ± 120 ms in reflex pull.

Figure 3 shows the time course of AV dCoP in AP and ML directions for voluntary and reflex pull. Both AV dCoP<sub>AP</sub> and AV dCoP<sub>ML</sub> start and end at zero, but after perturbation, AV dCoP<sub>AP</sub> exhibits a clear maximum (forward directed movement), whereas AV dCoP<sub>ML</sub> shows a small minimum (rightward directed movement). The time course of AV dCoP<sub>AP</sub> was similar between loading conditions except for an anticipatory response and reduced maximum during voluntary pull. No effect of loading was evident for AV dCoP<sub>ML</sub>.

Effects of shoulder contact on balance

The effect of light touch contact on balance was analyzed over the full time course of all the trials in terms of the SD of the dCoP in both AP and ML directions for voluntary and reflex pull loading conditions. Figures 4 and 5 show the effect of touch on SD dCoP<sub>AP</sub> and SD dCoP<sub>ML</sub>. The SD data exhibit maxima after perturbation and then decrease geometrically back toward the preperturbation baseline. A summary of the main effects and interactions for the four-way repeated-measures ANOVAs on SD dCoP with factors direction, loading, touch, time is given in Table 1.

Before perturbation, SD dCoP was significantly reduced by touch in both loading conditions for both directions. However, in the AP direction the effect of touch on SD dCoP was smaller during voluntary pull than reflex pull, whereas the opposite pattern was found for the ML direction. Also, SD dCoP was generally lower in the ML than AP direction as well as lower on reflex pull compared with voluntary pull. A significant interaction between loading and time reflected an increase in SD dCoP during voluntary pull in the 1-s interval before the perturbation that was not seen during reflex pull and was more pronounced in the AP direction (anticipatory response). Finally, the difference between voluntary and reflex pull was larger for SD dCoP<sub>AP</sub> than SD dCoP<sub>ML</sub> as indicated by a significant interaction between direction and loading.

Touch had a general effect on SD dCoP during the stabilization phase over the five time periods taken from dLoad onset \( (t = 0 \text{ s}; \text{see Table 1}) \). Analysis of the log-linearized SD dCoP time course starting immediately after the perturbation demonstrated that SD dCoP gradually dropped over time and was reduced with Light touch in both AP and ML directions. However, the reduction of SD dCoP with light touch was greater in the ML direction. The effect of touch increased over time and was greatest at the last time interval of the stabilization phase. Again as in the baseline phase before the perturbation, SD dCoP<sub>ML</sub> was generally smaller than SD dCoP<sub>AP</sub>.

The fit of the exponential decreasing function on the reduction of AP and ML SD dCoP during the stabilization phase after the perturbation was generally found to be quite satisfactory. Table 2 shows the average parameter estimates for the SD dCoP reduction function during stabilization for each experimental condition. The intercept parameter \( A \) (at \( x_0 \)) indicated greater SD dCoP in the period immediately after dLoad onset in the AP compared with the ML direction \( [F(1,10) = 107.48, P < 0.001] \). There were no effects of loading or touch on the intercept nor was there any interaction between touch and direction. However, a significant crossover between the two loading conditions as a function of direction was found with the intercept tending to be smaller during voluntary compared with reflex pull in the AP direction but larger in the ML direction \( [F(1,10) = 8.52, P = 0.015] \). Further, a significant interaction between loading condition and touch contact reflected a tendency for the intercept to be greater with light touch during voluntary pull, whereas the opposite was true for reflex pull \( [F(1,10) = 10.12, P = 0.01] \). Finally, there was a significant two-way interaction between direction, touch, and...
loading with a noticeably greater intercept during voluntary pull with light touch in the AP direction \( F(1,10) = 11.84, P = 0.006 \). This effect was more pronounced in the ML direction as indicated by a significant interaction between direction and touch \( F(1,10) = 6.45, P = 0.03 \). Further, a significant two-way interaction between direction, touch, and loading \( F(1,10) = 5.47, P = 0.04 \) demonstrated that light touch reduced the time constant of the reduction for reflex pull exclusively in the ML direction, whereas for voluntary pull, the touch effect was comparable in both directions. Generally, the time constant for the reduction of SD CoP$_{AP}$ was slightly shorter for reflex than voluntary pull. The opposite was true for the ML direction as expressed by a significant interaction between load and direction \( F(1,10) = 19.20, P = 0.001 \). Further, the effect of direction was significant \( F(1,10) = 44.64, P < 0.001 \) with a shorter time constant in the AP direction.

Under light touch conditions, the asymptote parameter \( C \) showed a significantly lower final value for SD CoP during stabilization \( F(1,10) = 46.24, P < 0.001 \). Moreover, the asymptotic value for SD CoP$_{ML}$ was lower than for SD CoP$_{AP}$ \( F(1,10) = 108.69, P < 0.001 \).

### Maintenance of shoulder contact

Figure 6 shows the mean force rate of the touch contact in the AP (AV dShear) direction. In general it will be observed that the AV function starts and ends at zero with fluctuations at and after perturbation. Before perturbation, there was no difference in AV dShear between voluntary pull and reflex pull. The same was true for AV dNormal (not shown).

After perturbation during stabilization, AV dShear showed a significant two-way interaction between direction, loading, and time \( F(4,40) = 5.43, P = 0.001 \). The sign of AV dShear was positive, indicating that the shoulder moved in the direction of load application.

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1 An additional analysis of peak-to-peak amplitude in each time period was performed to take explicit account of the biphasic form of the dCoP function. The results at \( t_0 \) closely followed those reported for the intercept.
different for voluntary pull and reflex pull. AV dShear was initially directed forward for voluntary pull and backward for reflex pull, indicating contrasting tendencies to sway forward and backwards at perturbation. Subsequently AV dShear changed in opposite directions for voluntary pull and reflex pull. In both loading conditions, the time course of AV dShear resembled an oscillation which started at perturbation and continued during stabilization after perturbation. In contrast, no difference between loading conditions was evident for AV dNormal. The time course of AV dNormal also tended to resemble a fluctuation that started at perturbation with force directed into the contact and tended to oscillate during stabilization. However, this effect was not statistically reliable.

**DISCUSSION**

Light touch with a static environmental contact point during quiet standing reduces body sway and associated fluctuations in ground reaction forces, as indexed by CoP variation (Holden et al. 1994; Jeka and Lackner 1994; Jeka et al. 1997). Light touch contact has also been shown to affect the postural response to forward sway produced by unpredictable backward displacement of the support surface (Dickstein et al. 2003). We used an unimanual pulling paradigm to investigate the time course of light touch contact effects on standing balance after predictable self-imposed (with voluntary pull) or unpredictable externally imposed (with reactive pull) perturbation. In both cases, perturbing forces at the right hand in the region of 20 N produced forward directed movement of CoPAP. We predicted light touch conditions, involving shoulder contact with a fixed reference, would improve the efficiency of reactive components of the response in reflex pull, facilitating earlier reduction in sway compared with no touch conditions. In contrast, we did not expect any effects of light touch on stabilization after voluntary pull under the assumption that feed forward anticipatory postural adjustments would already optimally stabilize body balance after the perturbation.

Our paradigm was successful in eliciting contrasts between voluntary pull and reflex pull in terms of reliably later grip, postural kinetics, and muscle responses in the reflex pull condition. Both loading conditions resulted in oscillatory fluctuations in the AP and ML components of the rate of center of pressure (dCoP). We took as our primary analysis measure the SD of dCoPAP and dCoPML computed over successive 1-s windows. In light touch conditions, the magnitude of the horizontal light touch contact normal force at the left shoulder averaged 2.7 N, which was somewhat greater than the 1 N vertical force threshold employed in previous studies (e.g., Holden et al. 1994). However, the shear force component of light touch contact in the AP direction relevant to the direction of perturbation was only 0.8 N and so small enough to be deemed “light.”

First considering variability, it may be observed that SD of both dCoPAP and dCoPML were significantly reduced with light touch immediately before the perturbation which replicates previous studies (Clapp and Wing 1999; Jeka and Lackner 1994) despite the use of an observation window of only 1-s duration in the present study. This result confirms a recent report (Rabin et al. 2006) of the sensitivity to light touch effects of CoP measures based on short observation windows. In the stabilization period after both voluntary pull and reflex
pull perturbations, we found SDs of dCoP<sub>AP</sub> and dCoP<sub>ML</sub> were also significantly lower with light touch. Further, light touch resulted in faster stabilization of SD dCoP under both loading conditions. More specifically, during voluntary pull light touch shortened the time constant of SD dCoP reduction in both directions, whereas during reflex pull, this was the case for SD dCoP<sub>ML</sub> only.

At perturbation, SD dCoP<sub>AP</sub> was greater with light touch in the case of voluntary pull, whereas no difference was found for reflex pull. This increase in SD dCoP<sub>AP</sub> at perturbation for voluntary pull with light touch represents a marked reversal of the light touch effect in the baseline period. Because SD dCoP<sub>AP</sub> was greater at perturbation with light touch for voluntary pull but reverts equally quickly to the same level after perturbation, it further emphasizes that light touch contact facilitates sway suppression faster in the case of voluntary pull.

The finding of a reduction in SD dCoP in voluntary pull is surprising in the sense that it indicates that the response to a self-imposed perturbation can be further improved with additional tactile sensory feedback about current postural sway despite anticipatory postural adjustments preceding the perturbation. A possible explanation could be that anticipation of the perturbation with light touch contact results in a different set of postural adjustments which more quickly restore the desired postural state.

There was a significant effect of loading condition on SD dCoP<sub>AP</sub> and SD dCoP<sub>ML</sub> before perturbation. Before perturbation variability was less in reflex pull than in voluntary pull. One possible reason is that these two conditions were not equivalent in terms of light touch contact. During reflex pull, participants lightly contacted the manipulandum with their digits to be able to detect load onset, whereas in the case of voluntary pull, contact with the digits was only made at the beginning of the pull. Thus in a sense, the initial postural state during reflex pull afforded two sources of light touch contact, the right hand and the left arm. Dickstein (2005) reported that bilateral light touch with the index fingers of both hands is more efficient in reducing postural sway than unilateral light touch with only one index finger as commonly used. Krishnamoorthy et al. (2002) reported that the exact positioning of unilateral light touch contact on the body affects the degree of sway reduction; however, the effect of bilateral light touch at homologous and nonhomologous body positions has not been reported. Although not designed for this purpose, our study is the first that indicates sway decreases with additional sources of light touch contact positioned on nonhomologous, bilateral parts of the body. The mechanism underlying integration of multipoint light touch contact information is one that we feel deserves further study.

The reduction of AV dCoP<sub>AP</sub> and the tendency for reduced SD dCoP<sub>AP</sub> variability seen during perturbation with voluntary pull compared with reflex pull (see Figs. 3 and 4) stand in contrast to a significantly higher load force rate (dLoad) in the voluntary pull condition. This suggests that predictive balance processes, which are indexed by the increase in AV and SD dCoP<sub>AP</sub> and CoP<sub>ML</sub> in the 1-s window before perturbation, effectively reduce the postural adjustment required to keep balance during the voluntary pull perturbation (even though the perturbation magnitude is greater in voluntary pull than reflex pull).

The interpretation of loading effects on AV and SD dCoP emphasize a contrast between the predictability of balance perturbation due to voluntary action with changes that lead load onset, and the more uncertain effects of an imposed disturbance, with changes after load onset. However, what is not clear from our results is whether these effects are fixed or develop, for instance, with familiarity with the task. Although we employed a blocked design that might have lent itself to an analysis of trial effects, relatively few trials per block were run so our study design would be insensitive to such effects and thus this question is left for future research.

It is interesting to note differences between voluntary pull and reflex pull in the time course of the average shear forces (AV dShear) during light touch after perturbation (see Fig. 6). A possible explanation is provided by Yamazaki et al. (2005),
who investigated CoP sway, but also bilateral trunk and thigh muscle activity, during rapid bilateral, asymmetrical changes of arm posture (right shoulder flexion and left shoulder extension) during upright stance. These rapid upper extremity movements resulted in a biphasic clockwise-anticlockwise upper trunk rotation, which were counteracted by early hip and thigh muscle contraction, confirming earlier findings of anticipatory postural adjustment preceding voluntary arm movements (Bouisset and Zattara 1981, 1987; Marsden et al. 1981). Further, large ML CoP variations were observed that were related to the rotation of the trunk. These results suggest that the antiphase directional fluctuations in shear force for voluntary and reflex pulls at the shoulder contact (see Fig. 6) originate from small counter-directional trunk rotations caused by the opposite directions of the right wrist movements.

Suppression of trunk rotation to maintain light touch might have “constrained” the postural control system, which limited the execution of the self-imposed voluntary pull perturbation. Thus the requirement of maintaining light touch contact may have acted as an additional task constraint to the postural control system during the preparation and execution of voluntary movement. A similar conclusion can also be drawn from the finding of Dickstein et al. (2003) that light touch results in a shift of mediolateral CoP velocity toward the contact plate during an external perturbation, an effect that was increased with stronger contact forces exerted by the participant.

Light touch contact is traditionally considered to enhance self-motion perception of body movements during upright stance and therefore to result in a reduction of postural sway. The location of light touch contact might serve as a spatial referent that affects body position sense based on proprioceptive information (Rabin and Gordon 2004; Reginella et al. 1999) and as a direct source of self-motion perception through transient shear forces at the contact point in the absence of a fixed spatial referent (Krishnamoorthy et al. 2002; Rogers et al. 2001). Both accounts imply that postural adjustments follow any force changes at the contact point (Jeka and Lackner 1995; Rabin et al. 2006). In contrast, if anticipatory postural adjustments are performed to maintain light touch, then one would expect postural responses to precede any changes of the contact force. However, such a temporal relation between light touch contact force and postural adjustments has not been reported up to now. We are now investigating if the effect of light touch contact switches from a facilitating to a “constraining” function under different postural and stimulus contexts and if the temporal relation between contact forces and postural responses is inverted.

The nature of the neural mechanisms contributing to the stabilization of upright stance is topic of continuing controversy. On one hand, it has been proposed that the intrinsic stiffness properties of the ankle are sufficient to ensure postural stability during quiet upright stance (Winter et al. 1998, 2001, 2003). On the other, Loram and Lakie (Lakie et al. 2003; Loram and Lakie 2002a,b) suggested that some neural mechanisms need to be actively involved in the control of ankle stiffness to modulate postural sway and to keep body balance stable (see also Morasso and Schieppati 1999). Further, this active neural intervention in the control of postural sway was assumed to be anticipatory (Fitzpatrick et al. 1996; Lakie et al. 2003; Loram and Lakie 2002a,b). In this context, the reduction of CoP variability during light touch as reported in the present article might be attributed to control mechanisms increasing ankle stiffness through muscle cocontraction, thereby reducing the movement degrees of freedom at the hip and ankle level to maintain light touch contact. Future research could examine ankle plantar and dorsi-flexor activity to evaluate this hypothesis.

Nevertheless, it is unclear on which neural level the presumed modulation of postural sway might take place. An account favoring lower level processing might assume that light touch at the shoulder changes the gain of the postural feedback loop by augmenting proprioceptive information relative to vestibular information during perturbation of upright stance with closed eyes (e.g., Ishida et al. 1997). However, light touch contact at the shoulder might serve as a stimulus that is processed by supraspinal neural circuits. For example, Jeka and Lackner (1995) inferred from the timing differences between finger tip contact forces, postural sway, and leg muscle activity that either long-latency reflex pathways or conscious anticipation might be involved in the control of postural sway.

The view that the facilitating function of light touch in postural control derives from its function as a “constraint” also implicitly assumes higher level neural processing of the light touch contact. For example, Riley et al. (1999) demonstrated that light touch only reduces variability of postural sway if it is declared relevant to the task. Thus only participants who were instructed to precisely control light touch showed a reduction of sway variability compared with a no touch condition. This finding was subsequently corroborated in a study (McNevin and Wulf 2002) that showed that only an external attentional focus that is directly related to the finger lightly touching an object resulted in reduction of postural sway. Thus light touch may be considered a constraint to the postural system in the sense that it defines a limit on body sway to preserve light touch. If keeping light touch close to a set value or within a certain range acts as the goal of a “supra-postural task,” predictive control processes, the function of which is to reduce variability of light touch, can be assumed to be in operation. Also during self-imposed perturbations, the predictive control processes will serve to anticipate the disturbance and minimize the impact on balance. Maintaining light touch during a voluntary movement increases the coordinative complexity of the postural task thereby abolishing the facilitating effect of light touch.

In our present study, we used a static spatial referent to provide light touch contact at the left shoulder. Our findings can be interpreted as light touch affecting participants’ postural responses during the perturbation as a constraint of the postural goal state that has to be taken into account when preparing appropriate postural adjustments in response to a perturbation of balance. To discriminate between an account that assumes that light touch improves stability through sensory feedback of small transient shear forces at the contact spot and an account that suggests that light touch imposes a constraint to the postural control system during a perturbation of balance, it seems reasonable to follow the suggestion of Krishnamoorthy et al. (2002), who demonstrated that given strong enough shear forces the effect of light touch is not linked to the availability of a fixed spatial reference. We are currently testing the effect of attaching a tactile stimulator to apply shear forces to the skin which would provide information about body sway. By adjust-
ing the spatial gain of the stimulator the intentional nature of the force feedback on balance stability will be explored.

We conclude that the immediate response to a voluntary perturbation and the stabilization after both a voluntary and a reflex perturbation are altered by light touch. To maintain light touch, CoP fluctuations are differentially modulated in AP and ML directions after a voluntary perturbation. Thus light touch influences CoP fluctuations not only by providing a sensory spatial reference but also by constraining the movements of the body after a perturbation.

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R E F E R E N C E S


