Gait & Posture 38 (2013) 477–482

Contents lists available at SciVerse ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Does postural stability affect grasping?

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ARTICLE INFO

Article history:
Received 11 July 2012
Received in revised form 14 January 2013
Accepted 19 January 2013

Keywords:
Grasping
Posture
Instability
Dual-task

ABSTRACT

We examined whether challenging upright stance influences the execution of a grasping task. Participants reached to grasp a small sphere while standing either on a stable surface or on foam. Before reaching for the sphere, participants exhibited more body sway and greater fluctuations in the centre of pressure when standing on foam. While reaching for the sphere, the overall body posture changed less when standing on foam than when standing on the stable surface. The digits' and wrist's movements towards the sphere were no different when standing on foam than when standing on the stable surface. Presumably, the redundancy in the way movements can be performed is exploited to choose the most suitable changes in joint angles to achieve the desired movements of the digits under the prevailing conditions.

1. Introduction

When reaching to grasp an object while standing, people simultaneously move their digits to appropriate positions on the object and maintain a stable upright posture. The coordination between whole-body posture and arm movements has been studied extensively [1–3]. Humans adjust their posture in anticipation of the arm movement's influence on postural stability [4–7] bearing in mind how to best lift the target object considering its properties [8,9]. Thus the whole-body posture is certainly influenced by the arm movement. However, the reverse has hardly been studied: how constraints imposed by posture influence a simultaneously executed arm movement, and in particular the movements of the wrist and fingertips during a reaching-to-grasp action. The duration of grasping movements is adjusted to postural demands in a task in which postural stability is evidently critical: rock climbing [10]. But are reach-to-grasp movements also affected by postural constraints when the emphasis on posture is less extreme than in rock climbing?

Grasping movements can be influenced by the target object's properties [11,12], its visibility [13], the presence of obstacles [14] and what the actor intends to do with it [15]. A more fragile object or one that is partly hidden is grasped more carefully: with a larger maximal grip aperture [13] and slower movements [12]. In order to examine whether increased postural demands influence reach-to-grasp movements, we let participants perform such movements while standing either on a stable or an unstable (foam) surface. Standing on foam is expected to increase body sway. Consequently, participants may have to execute the reach-to-grasp movements more carefully, as would be reflected in more curved wrist paths [16], slower grasping movements and larger maximal grip apertures that occur earlier in the movement (reviewed in [17]). Alternatively, adopting the best posture may be such an integral part of the reach-to-grasp movement, that the posture is adjusted to the kind of surface without this affecting the movements of the digits. In that case movement speed, maximal grip aperture and path curvature should not depend on the support surface, but the posture should be adjusted to facilitate the execution of the 'normal' reach-to-grasp movement.

2. Methods

2.1. Participants

Seventeen healthy right-handed volunteers (14 women, 3 men; age: 31 ± 9 years; height: 168 ± 10 cm; weight: 61 ± 14 kg) participated in the study. They all had normal or corrected-to-normal vision. The experiment is part of a program that has been approved by the local ethics committee.

2.2. Apparatus

Kinematics of the arm and trunk were recorded at 150 Hz with an Optotrak motion tracking system (Northern Digital, Canada). Small clusters with three infrared markers were fixed to the nails of the thumb and index finger. Additional infrared markers were fixed to the wrist, hip and forehead. A 3D custom-made force plate was used to measure the centre of pressure (CoP) at 150 Hz. Participants either stood directly on the force plate (*stable surface*) or on a piece of foam (*foam*; length and width: 40 cm; height: 15 cm with no load, and about 10 cm when compressed

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http://dx.doi.org/10.1016/j.gaitpost.2013.01.016

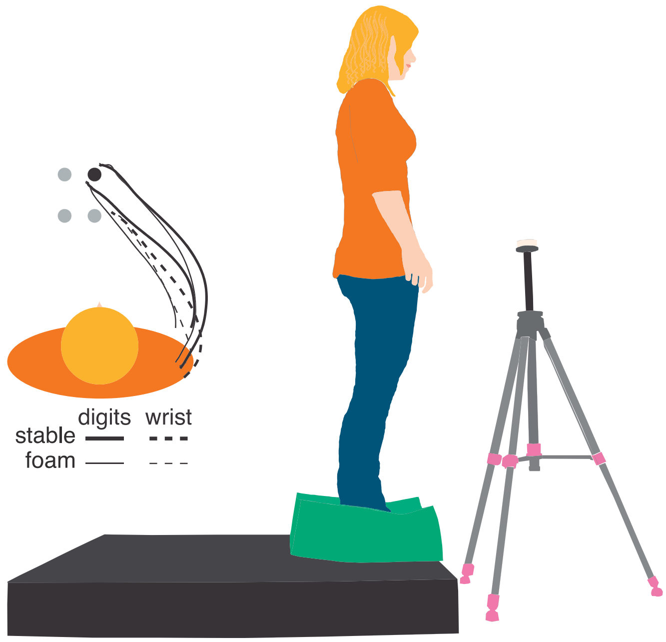

Fig. 1. Schematic side-view of the set-up showing a participant standing on foam in front of the tripod. At the left a simplified schematic top-view is shown. Examples of the paths of one participant's digits and wrist when reaching to grasp the object placed at the far distance along the midline are superimposed on this view.

by the weight of the participant; density: 35 kg/m^3). Standing on foam is a common method to induce postural instability [18–20].

A sphere (4.5 cm diameter, 123 g mass) was placed in a small indentation at the top of a height-adjustable tripod. The tripod was elevated when the participant was standing on the foam so that the sphere was always at hip height (Fig. 1). The sphere and tripod were placed at one of four different positions: two reaching distances (*far*, *close*) and two lateral locations (centre, *side*). At the far distance the participant could just reach the sphere with a fully extended arm without leaning forward. At the close distance the participant considered the arm to be half extended. The centre locations were along the participant's midline. The side locations were 20 cm to the left (Fig. 1).

2.3. Procedure

Participants stood barefoot on the force platform, with their feet parallel and about 20 cm apart, and with their arms by their side. The sphere and tripod were either positioned straight in front of the participant or in front and to the left, depending on the condition. The experimenter gave a verbal signal indicating the initiation of data collection. After 4 s, another verbal signal indicated that the participant should start moving his or her right arm to grasp the sphere between the index finger and thumb, lift the sphere, put it back on the tripod, and move the arm back to his or her side. Each of the eight conditions (2 surfaces; 4 object positions) was presented in a block of five consecutive trials. Half the participants started with the four blocks on the stable surface and the other half started with the four blocks on the foam. The blocks for the different object positions were presented in random order.

2.4. Data analysis

For calibration, we measured the markers' positions while the participant held an additional marker between the thumb and index finger. The position of this additional marker with respect to the clusters on the digits was used to determine the coordinates of the fingertips from measured positions of the clusters. If markers of the clusters were invisible for more than 10 frames when the digits were close to the sphere, the trial in question was discarded. If this occurred in more than three trials for the same condition and participant, all data of this participant were discarded.

We calculated the linear *velocity of the wrist* by numerical differentiation of the wrist's marker position. *Grip aperture* is the distance between the two fingertips. *Movement onset* was determined with a speed threshold of 0.5 cm/s for the wrist marker. The *moment of the grasp* was determined using the Multiple Sources of Information method [21]: the average position of the two digits had to be less than 7 cm from the centre of the object; the wrist's velocity had to be below 1 cm/s; the grip aperture had to be between 4.0 and 5.8 cm; and the probability of a moment being the end of the movement decreased over time.

Movement time was defined as the time between movement onset and the moment of the grasp. *Maximal grip aperture* and *wrist peak velocity* were defined as the largest values during the reach-to-grasp movement. We also calculated the *relative time to maximal grip aperture* and *to wrist peak velocity*, which was the time from movement onset to the time at which these maxima occurred, as a percentage of the movement time. *Grip orientation* was determined from the projection on the horizontal plane of the line connecting the fingertips at the moment of the grasp. The *wrist's net displacement* is the euclidean distance between the wrist's position at the start and that at the end of the movement. In order to quantify the curvature of the reaching trajectories, we calculated how much longer the wrist's path was than its net displacement (expressed as a percentage of that distance; *wrist's extra path*).

We also determined variables that describe the standing posture, such as the *hip's* and *head's net displacements*, and the standard deviation of the hip's angular position with respect to the foot (*sway*). From the ground reaction forces we determined the net displacement and the standard deviation of the position of the *Centre of Pressure* (CoP). The sway and standard deviations were determined along the anteroposterior (AP) and mediolateral (ML) axes.

We divided each trial into three phases: a *postural phase* (all data collected until 507 ms before the onset of the reach-to-grasp movement), an *anticipatory phase* (the last 500 ms before the onset of the reach-to-grasp movement) and a *movement phase* (during the reach-to-grasp movement). The average and standard deviation of each dependent variable was determined for each condition and participant. Figs. 2 and 3 show the means of these values for each condition, with error bars showing the within-subject variability. The variability across the subjects' average values is also shown (averaged across object positions) for the grasping measures. Differences between conditions were evaluated using 2 (surfaces) $\times$ 2 (reaching distances) $\times$ 2 (lateral locations) repeated measures ANOVAs on the average data per participant and condition. For the variables obtained during the postural phase only the factor "surface" was considered.

3. Results

Based on criteria described earlier (see Section 2), all the data of nine participants and a total of seven trials of the remaining eight participants were discarded. Another three participants' data was not included in the analyses of the variables concerning the wrist, because the wrist marker was often invisible at critical moments. Their data was not conspicuously different from that of the other five participants on other measures. Their wrist marker was not particularly often invisible in certain conditions. For clarity, we present all effect sizes in the figures and all statistical evaluation in Table 1.

3.1. Postural phase

Not surprisingly, the standard deviation of the hip's angular position and of the CoP's position (Fig. 2a–d) was more variable when standing on foam than when standing on the stable surface.

3.2. Anticipatory phase

Again, the CoP's position was more variable when standing on foam (Fig. 2c and d). The ML variability of the CoP's position was also influenced by the lateral location and the reaching distance. Both for the ML and the AP variability of the CoP's position, there were interactions between the support surface and the lateral location: there were smaller differences between the support surfaces when the object was placed on the left (Fig. 2c and d). The net AP CoP displacement was larger when standing on foam (Fig. 2e) and depended on the reaching distance. The net ML CoP displacement depended on the lateral location and on the reaching distance. There were significant interactions between support surface and lateral location for both the net AP and ML CoP displacements, showing that the effects of the support surface depend on the lateral location.

3.3. Movement phase

3.3.1. Posture

During the movement phase, the net AP and ML CoP displacements were smaller when standing on foam (Fig. 2e and f), were

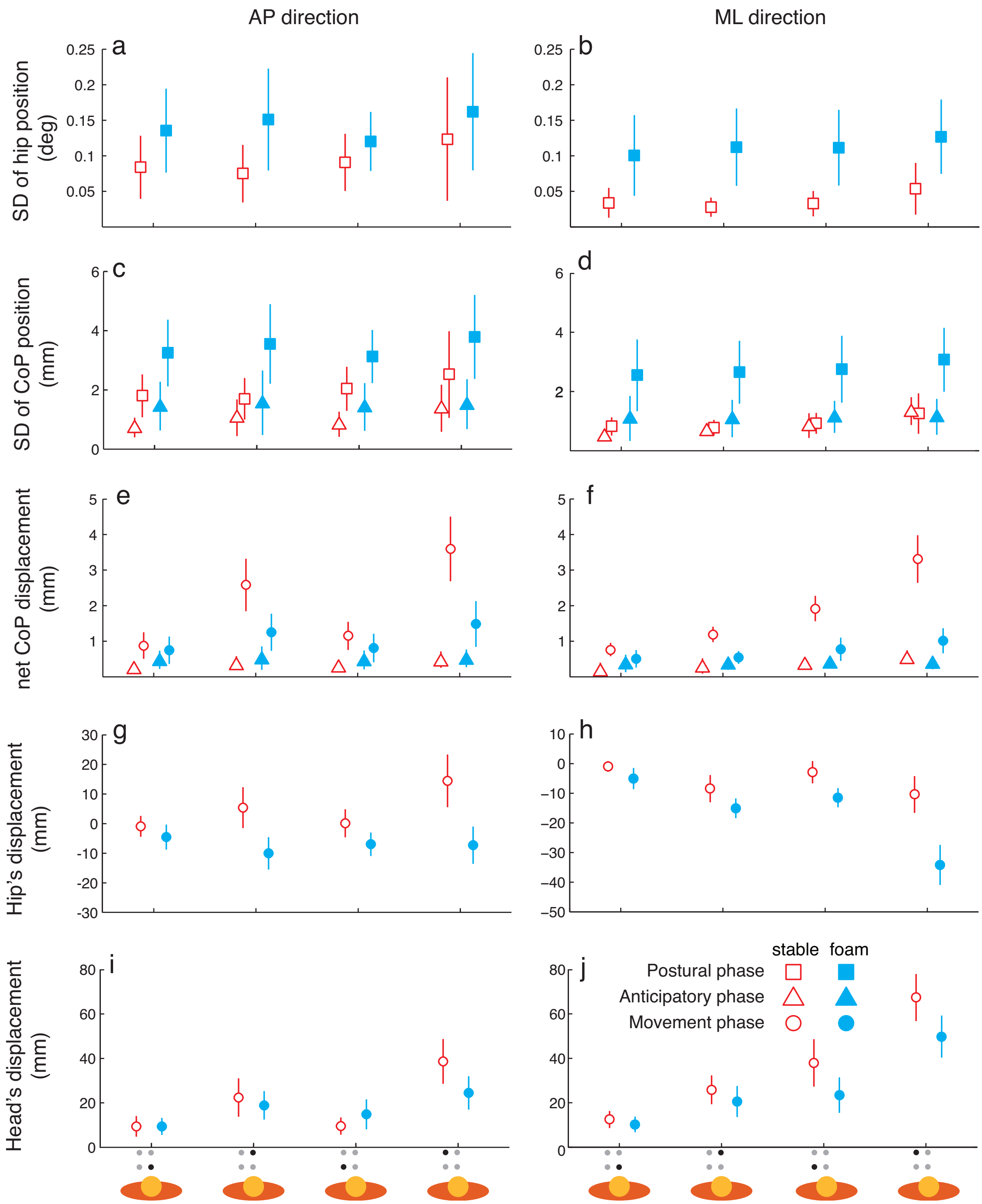

Fig. 2. Influence of support surface and object position on the standard deviation of the hip's anteroposterior (AP) and mediolateral (ML) position during the postural phase (a, b), on the standard deviation of the AP and ML CoP position during the postural and anticipatory phase (c, d), on the net AP and ML displacement of the CoP during the anticipatory and movement phase (e, f), and on the AP and ML hip's (g, h) and head's (i, j) net displacement during the movement phase. Positive is to the front (e, g, i) and to the left (f, h, j). Error bars in this and subsequent figures represent the average standard deviation within the replications of each condition (within-subject variability).

affected by the reaching distance and the lateral location, and there were significant interactions between the support surface and the reaching distance. There was a significant interaction between support surface and lateral location for the net ML CoP displacement; participants responded less to differences in the object's position when standing on foam.

The support surface also influenced the hip's linear AP and ML displacements; participants moved their hips more to the right and to the back when standing on the foam than when standing on the stable surface (Fig. 2g and h). For the hip's ML displacement we found a significant effect of the reaching distance as well as significant interactions between support surface and lateral location, between support surface and reaching distance, and a three-way interaction. The interactions can be interpreted as there being larger differences between the support surfaces when the sphere was placed at the far and side locations. For the AP displacement we found a significant interaction between support surface and reaching distance, and between lateral location and

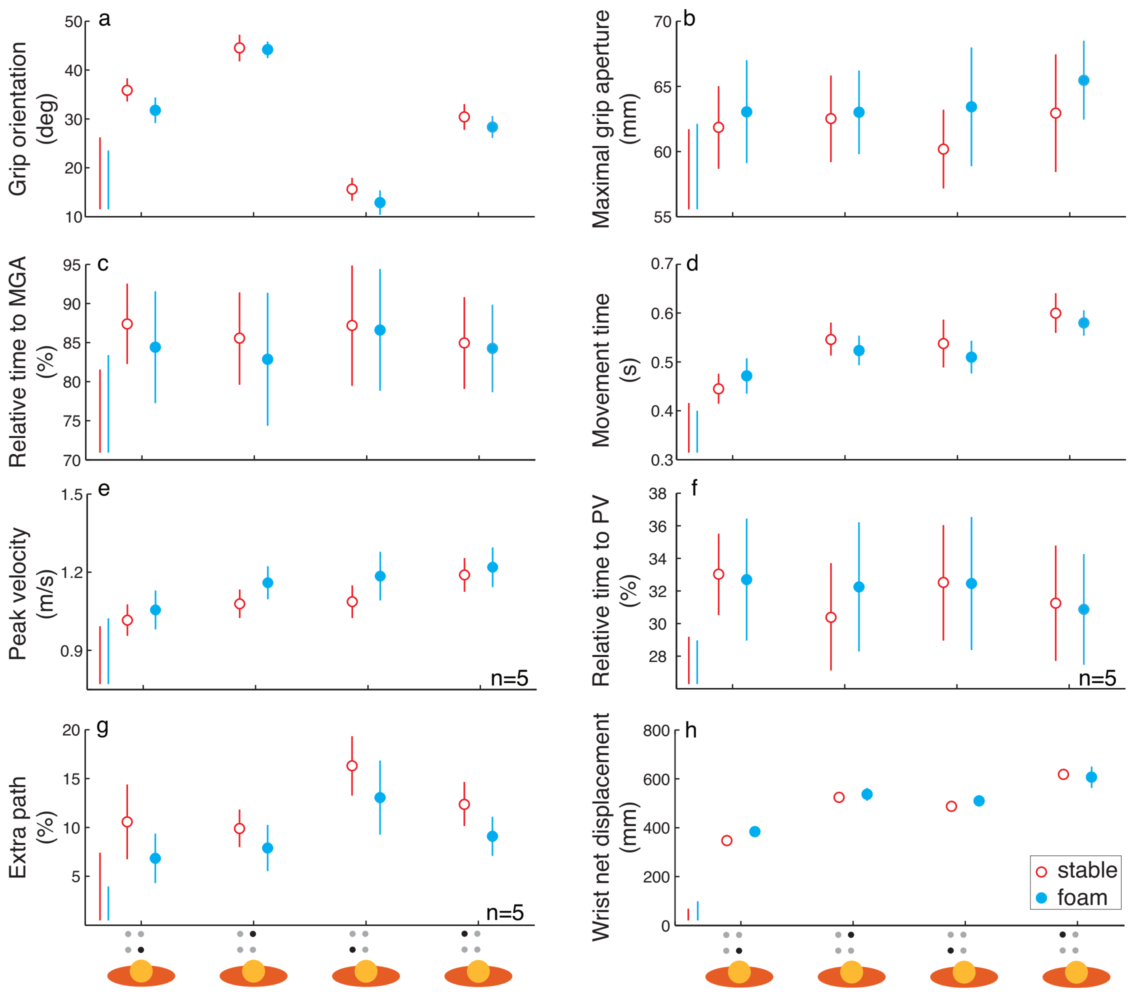

Fig. 3. Influence of support surface and object position on grip orientation (a), maximal grip aperture (b), relative time to maximal grip aperture (c), movement time (d), the wrist's peak velocity (e), relative time to peak velocity (f) and the wrist's extra path (g). A grip orientation of 0° means that the thumb and index finger are both in the sagittal plane, with the thumb nearer the body, and a positive rotation is clockwise (as seen from above). Bars in the lower left corner of each panel represent the standard deviation across subjects for the stable (red) and foam (blue) condition (averaged across object positions). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reaching distance. The former interaction could again arise from a larger difference between the support surfaces when the object was placed far away.

The ML displacement of the head was influenced by the support surface. The head moved less far to the left when participants were standing on foam (Fig. 2j). Both AP and ML head displacements were affected by the lateral location and by the reaching distance (Fig. 2i and j), and there were lateral location by reaching distance interactions. For the AP head displacement there was also a three-way interaction.

3.3.2. *Grasping*

Fig. 3 summarizes the effects on the grasping parameters. A more clockwise grip orientation was used when the object was further away or further to the right. There was also a significant interaction between lateral location and reaching distance.

Movement time was longer when the object was placed further to the left or further away. There was a significant interaction between support surface and lateral location, suggesting that the support surface had a stronger influence when the object was placed further to the left. There was also a three-way interaction. Importantly, movement time was only longer when standing on foam when the object was placed at the closest position.

The lateral location influenced the wrist's peak velocity, net displacement and extra path (Fig. 3). Participants moved faster along a more curved and longer path when the object was on the left. The net wrist displacement was obviously affected by the reaching distance. Wrist velocity profiles were very similar for the two surface conditions (Fig. 4). No significant effects of surface condition were found for the maximal grip aperture, net wrist displacement, extra path, or relative time to maximal grip aperture or to wrist peak velocity. The within-subject variability was similar for the two support surfaces (error bars in Fig. 3), as was the variability across subjects for most measures (bars in the lower left of each panel of Fig. 3). The variability in the extra path across subjects appears to be smaller when standing on foam.

4. Discussion

Our main finding is that challenging upright stance by altering the support surface has very little influence on the execution of a reach-to-grasp movement. Grip aperture and its timing did not depend on the support surface. Neither did the wrist's displacement and path, although there was a trend towards straighter paths when standing on foam. The movement time was longer when standing on foam for one of the four object positions, but this

Table 1
Statistical evaluation of whether surface, location and distance influence various parameters during the three phases. *F* values are given for all significant main effects and interactions. Location and distance were not considered for the postural phase. No significant effects were found for the maximal grip aperture, relative time to maximal grip aperture or relative time to wrist peak velocity (movement phase). Bold fonts indicate effects involving the support surface. SD: standard deviation.

		AP axis	ML axis
Postural phase			
SD hip's angular position	**S**	$\mathbf{F\ (1,7)=7.2}^{*}$	$\mathbf{F\ (1,7)=21.3}^{**}$
SD CoP	**S**	$\mathbf{F\ (1,7)=35.3}^{***}$	$\mathbf{F\ (1,7)=25.9}^{***}$
Anticipatory phase			
SD CoP	**S**	$\mathbf{F\ (1,7)=15.5}^{*}$	$\mathbf{F\ (1,7)=10.3}^{*}$
	L		$F\ (1,7)=8.8^{*}$
	D		$F\ (1,7)=13.8^{*}$
	S × L	$\mathbf{F\ (1,7)=6.3}^{*}$	$\mathbf{F\ (1,7)=23.5}^{**}$
CoP displacement	**S**	$\mathbf{F\ (1,7)=12.4}^{*}$	
	L		$F\ (1,7)=11.9^{*}$
	D	$F\ (1,7)=7.1^{*}$	$F\ (1,7)=22.4^{**}$
	S × L	$\mathbf{F\ (1,7)=6.0}^{*}$	$\mathbf{F\ (1,7)=28.5}^{***}$
Movement phase			
CoP displacement	**S**	$\mathbf{F\ (1,7)=17.4}^{**}$	$\mathbf{F\ (1,7)=41.2}^{***}$
	L	$F\ (1,7)=14.9^{**}$	$F\ (1,7)=59.9^{***}$
	D	$F\ (1,7)=48.4^{***}$	$F\ (1,7)=64.9^{***}$
	S × D	$\mathbf{F\ (1,7)=14.2}^{*}$	$\mathbf{F\ (1,7)=20.3}^{**}$
	S × L		$\mathbf{F\ (1,7)=28.3}^{***}$
Hip's displacement	**S**	$F\ (1,7)=20.6^{**}$	$\mathbf{F\ (1,7)=12.7}^{*}$
	D		$F\ (1,7)=14.9^{*}$
	S × L		$\mathbf{F\ (1,7)=6.5}^{*}$
	S × D	$\mathbf{F\ (1,7)=9.5}^{*}$	$\mathbf{F\ (1,7)=15.7}^{**}$
	L × D	$F\ (1,7)=7.1^{*}$	
	S × L × D	$\mathbf{F\ (1,7)=7.8}^{*}$	
Head's displacement	**S**		$\mathbf{F\ (1,7)=10.7}^{*}$
	L	$F\ (1,7)=39.4^{***}$	$F\ (1,7)=49.9^{***}$
	D	$F\ (1,7)=9.4^{*}$	$F\ (1,7)=35.1^{***}$
	L × D	$F\ (1,7)=16.4^{*}$	$F\ (1,7)=29.2^{***}$
	S × L × D	$\mathbf{F\ (1,7)=9.7}^{*}$	
Grip orientation			
	L	$F\ (1,7)=253.8^{***}$	
	D	$F\ (1,7)=126.5^{***}$	
	L × D	$F\ (1,7)=8.8^{*}$	
Movement time			
	L	$F\ (1,7)=24.0^{**}$	
	S × L	$\mathbf{F\ (1,7)=7.1}^{*}$	
	S × L × D	$\mathbf{F\ (1,7)=15.0}^{*}$	
Wrist's peak velocity	L	$F\ (1,4)=10.3^{*}$	
Wrist's extra path	L	$F\ (1,4)=8.3^{*}$	
Wrist's displacement	L	$F\ (1,4)=123.2^{***}$	
Wrist's displacement	D	$F\ (1,4)=108.4^{***}$	

S: surface; L: location; D: distance; ×: interaction.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.01$.

was not even the most demanding position. The absence of increases in movement time and maximal grip aperture, or of changes to the wrist's path, when standing on foam suggests that subjects were confident that they could adjust their posture to perform the reach-to-grasp movement normally. The similar variability across the two surfaces, both within and across subjects, confirms that they could do so. Object position also influenced grasping in the expected manner [22–24] irrespective of the support surface.

In contrast to the lack of effects on grasping, posture was altered when standing on foam. Participants swayed more when standing on foam during the postural phase and then leaned less towards the object, probably to ensure that they could cope with the destabilizing effect of the arm movement [2]. These findings are consistent with previous reports that standing on foam increases sway [19,25], and decreases leaning towards a target object [17]. Thus, the stability provided by the support surface is clearly considered when planning and executing the grasping movement.

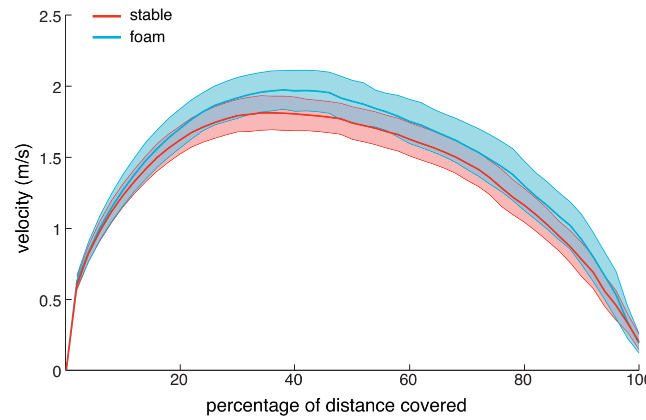

Fig. 4. Average wrist's velocity profile for the two support surface conditions. The averaging was done as a function of the percentage of the distance covered by the wrist. The shaded area indicates the average standard deviation within the replications (averaged across subjects and conditions). The two profiles are similar, although the velocity is slightly higher in the foam condition.

The critical factor for successfully performing our grasping task was to move the digits to suitable positions on the object [16]. In our study, how the digits moved to such positions did not change when the whole-body posture was adjusted to cope with the surface stability. This supports the idea that adopting the best possible postures to maintain one's balance during the reach-to-grasp movement is an integral part of the movement. Posture is modulated according to the type of surface without this affecting the movement of the digits. Previous studies have shown that posture can be modified to maintain a normal execution of arm movements when reaching in microgravity [26], when additional loads perturb whole-body reaching movements [27], or just to improve performance in a pointing task [28]. However, the arm movement will only be performed normally when there is ample freedom to modify one's posture. If one does not have such freedom, picking a suitable posture will no longer be easy and one will not always be able to move the arm in the same manner. For instance, in rock climbing, the duration of grasping movements does depend on the postural demands [10]. In our study, the changes in posture did not even affect the duration of the reach-to-grasp movement. Thus it would appear that moving the digits to appropriate positions on the object and maintaining a stable upright posture are extremely well coordinated, with priority being given to the most important aspect of the action at the time. In our study, the digits' movements were presumably considered to be more important than adopting a particular posture.

The postural adjustments to the support surface in our reach-to-grasp task were not just responses to the inertial influence of extending the arm, because they started well before the grasping movement started. This supports the notion [29,30] that postural considerations are fully integrated in planning the upcoming arm movement. Presumably, the redundancy in the way movements can be performed is exploited to choose the most suitable changes in the body's joint angles to achieve the desired movements of the digits under the prevailing conditions, so that different postural configurations are chosen for the same movements of the digits when standing on different surfaces.

Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement number 214728-2 and from the

Alexander S. Onassis public benefit foundation under grant agreement F ZH 016/2011-2012.

Conflict of interest statement

None declared.

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