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Visual and postural control of an arbitrary posture: The handstand

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Abstract

The aim of this study was to increase our understanding of postural regulation by analysing an arbitrary posture – the handstand. We assessed the relative influence of peripheral vision and central visual anchoring on the postural balance of gymnasts in the inverted-stand posture. Displacements of the centre of pressure, the angles between the body segments, and the gymnast's height in the handstand were analysed. Postural regulation in the handstand appeared to be organized according to a system similar to that in erect posture, with three articular levels suggesting the existence of a typical organization of human posture. Moreover, both intra-modal (central and peripheral vision) and inter-modal sensory systems (vision and other balance systems) contributed to the postural regulation. The results are interpreted in terms of an ecological approach to posture in which postural regulation can be considered as an emergent phenomenon.

Keywords: *Vision, posture, regulation, inter-sensory, handstand, gymnastics*

Introduction

Postural balance is regulated by the sensory systems, including the vestibular, proprioceptive, and visual systems. An understanding of the role of vision in postural regulation helps to understand how humans manoeuvre in their environment. This has been the implicit or explicit motive of many studies on regulation in erect posture in static and dynamic conditions or during supra-postural tasks (Bardy, Warren, & Kay, 1996; Oullier, Bardy, Stoffregen, & Bootsma, 2002; Stoffregen, Smart, Bardy, & Pagulayan, 1999; Warren, Kay, & Yilmaz, 1996).

From the perspective of the ecological theories initiated by Gibson (1966), postural regulation occurs through a process of perception–action circularity – that is, by the management of one flow with one force. According to this circular theory, perception is the precondition for postural regulation and posture both functions as an aid to visual perception and supports the performance of supra-postural tasks (Balasubramaniam, Riley, & Turvey, 2000; Bardy, Warren, & Kay, 1999; Marin, Bardy, Baumberger, Fluckiger, & Stoffregen, 1999; Marin, Bardy, & Bootsma, 1999; Ouiller *et al.*, 2002; Stoffregen *et al.*, 1999; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000).

Some studies on posture have demonstrated that visual information has a key role in postural control because when participants in erect stance close their eyes, postural oscillations increase (Edwards, 1946). Visual information is of primary importance, since it enables us to detect the direction of our movement and control its trajectory (Bardy *et al.*, 1996; Li & Warren, 2000, 2002; Stoffregen, 1985; Warren & Hannon, 1988). Visual cues can even compensate for a loss of postural control induced by muscular fatigue (Vuillerme, Nougier, & Prieur, 2001).

The optical flow contains invariants that specify information about the individual's environment: movement parallax and optical expansion or contraction (Guerraz, Thilo, Bronstein, & Gresty, 2001; Stoffregen *et al.*, 1999). These two optical invariants appear to provide the basis for visuo-postural control (Warren *et al.*, 1996). The question then arises as to whether these invariants can be explained by the structural organization of the receptor or by the structure of the information itself. Some studies have proposed the theory of peripheral retinal predominance to account for information on our own movements and have shown that peripheral perception includes central information, and not the inverse (Habak Casanova, & Faubert, 2002). However, Stoffregen (1985, 1986) concluded that the structure of the flow was more significant than the retinal localization. The lamellate flow informs us about our own movements and, in a general way, peripheral predominance would thus be related to the most

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current, natural situations. Body movement on the anterior-posterior axis creates a lamellate flow, which then appears preferentially to the retinal periphery. Warren and Kurtz (1992) defined this phenomenon by first assuming functional sensitivity: the retina has different degrees of sensitivity to information according to the perceptive area. However, Bardy *et al.* (1999) emphasized the finding of retinal invariance. Central and/or peripheral vision can use radial and/or lamellate flow to control body displacements. But peripheral vision is more sensitive to movements in the surrounding environment (Redfern, Yardley, & Bronstein, 2001) and can detect the direction of two points in two different visual areas better than central vision (Habak *et al.*, 2002). In poor visual circumstances, the peripheral area collects central information and even facilitates central measurement and not the inverse; on the other hand, central vision is better in the detection of slow movements (Habak *et al.*, 2002).

When Gibson (1966) first pointed out that we must perceive to move and we must move to perceive, he signalled a paradox: we must both stabilize posture and create a minimum of movement to create the necessary flow to control this stability. Riccio and Stoffregen (1988) demonstrated that the upright posture is regulated in a robust region, in which the regulation is automatic, and an adaptive region, in which exploratory strategies are used to redefine the appropriate automatic strategies arising from the robust region. Others have described the organization of the erect postural regulation as a three-level hierarchical system that starts at the ankles, then moves to the hips and, finally, the knees (Nashner & McCollum, 1985).

In all of the above-cited works, the posture under study was "natural", the result of our species' phylogenetic history and ontogenesis: upright posture. However, humans sometimes adopt unusual postures, as is often the case in sports. The study of these sport-specific postures not only increases our understanding of athletic performance, but also provides insights into the nature of visuo-postural regulation in humans. In this study, we selected the handstand as the unusual posture. To appreciate how the study of the handstand might enlighten us regarding the intricate relationships between vision and postural control, it is first necessary to describe its unique characteristics.

The body organization for the handstand is similar to that for upright posture, and it seems that transfers occur between the lower and upper limbs during handstand performance (Clement & Rezette, 1985). However, the handstand involves the following characteristics compared with the upright position: the support surface is reduced and the distance between the ground and the centre of gravity is greater because of the alignment of the arms in the extension of the body, which increases instability (Slobounov & Newell, 1996). The handstand requires unusual muscle activity from the upper limbs, since they adopt the anti-gravity role of the lower limbs. The anterior-posterior deviations in the handstand are greater than in upright posture (Slobounov & Newell, 1996). Although the function of the muscles in the upper limbs is more precise, it is less resistant to fatigue than lower-limb function. Finally, as described by Nashner and McCollum (1985), the configuration of the handstand is different from that of the erect posture because four joints are used (wrists, elbows, shoulders, and hips) instead of three and this requires a specific postural coordination.

In both erect posture and the handstand, the centre of pressure oscillations increase when vision is occluded, reaffirming the influence of vision (Clement & Rezette, 1985). However, postural performance in the handstand is similar with eyes open and closed when the head is in flexion compared with the initial position, which highlights the major effect of head position and the associated neck reflex (Asseman & Gahéry, 2005). In the standard position, the role of gaze appears to be more important in the handstand than in erect posture because of the head's proximity to the ground (Clement & Rezette, 1985). In addition, Lee and Lishman (1975) showed that the closer the visual target is, the more the anterior-posterior oscillations decrease. Since the visual environment is closer in the handstand than in erect posture because of the head's proximity to the ground, the handstand should be better controlled visually than the upright posture. Also, Clement, Pozzo, and Berthoz (1988) found that gaze is fixed on a point located approximately 5 cm in front of the wrists in the middle of the space located between the two hands. This corresponds to a visual anchoring point called the "cliff edge". These same authors explained that gymnasts associate this point with the optimal vertical projection of the centre of gravity around which the stability of the handstand is controlled.

Many studies have characterized the handstand by providing detailed postural descriptions (Kerwin & Trewartha, 2001; Slobounov & Newell, 1996) or by analysing the central anchoring (Clement & Rezette, 1985; Clement *et al.*, 1988). To date, however, no study has investigated the handstand from the perspective of ecological theory. The aims of this study were thus to determine whether the postural organization of an unusual posture, the handstand, is similar to that of the erect posture and to assess the respective contributions of peripheral vision and central anchoring to the maintenance of this balance.

Methods

Participants

Ten male gymnasts aged 18–25 years (mean age 22.1 years, $s = 3.0$) volunteered to participate in the study. Their mean height was 1.71 m ($s = 0.07$) and their mean mass was 68.3 kg ($s = 9.5$). All had normal vision, were able to maintain a handstand for more than 30 s, and had participated in national or international gymnastics competitions in the year preceding the study.

Task

The gymnasts performed handstands on two horizontal bars and had to maintain the position for 15 s. The horizontal bars were chosen to facilitate postural maintenance, given the task complexity, and to standardize the hand position. The bars were circular with a radius of 3.5 cm and arranged in parallel 46 cm apart (this corresponds to the platform size described below).

Apparatus

For each test, the participants performed the handstand on a horizontal stabilometric platform (46 × 46 cm) equipped with three strain gauges (QFP System) (Figure 1), which recorded the variations in the centre of pressure (in millimetres) along the anterior-posterior (Y) and medio-lateral (X) axes. The acquisition frequency was 50 Hz.

The handstand trials were filmed in the sagittal plane using a video camera (frequency 50 Hz) placed 6 m from the gymnasts and 1.4 m from the ground. Before video acquisition, seven reference markers were placed on the left side of the gymnasts, on the projected joint centre of the wrist, elbow, shoulder, hip, knee, and ankle; the seventh was fixed at the point where the end of the fingers touched the upper edge of the platform (Figure 1). The markers were used to identify angles, distances, and angular movements of the different segments of the gymnasts in the sagittal plane. We used our own software (3CLIC©) for the video analysis, which consisted of sampling and analysing the video at 50 Hz. Standard trigonometric relationships were used to calculate segment angles from the vertical and horizontal coordinates of the joint markers.

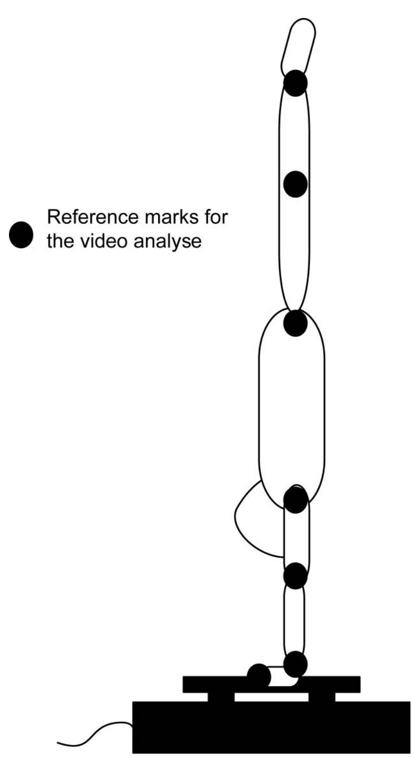

Figure 1. Posture of gymnast in experimental conditions.

Procedures

The gymnasts held the handstand in four conditions: (i) eyes open, (ii) eyes closed, (iii) in central dark (only central anchoring was visually available), and (iv) in peripheral dark (only peripheral cues were visually available). Three trials per condition were performed.

In all the conditions, the gymnasts were instructed to maintain the handstand as stable as possible, without any instructions regarding visual information. For the last two conditions, the participants maintained the handstand in a dark room. The central visual anchoring was identified by a reflective sticker placed 5 cm in front of the wrists, based on the conclusions of Clement and colleagues (1988). The markers for peripheral vision were reflective stickers placed in the peripheral environment and on the participant's arms. The central and peripheral variables of flow were thus isolated from each other to allow the identification of their respective influences.

Data analysis

The eyes open condition was used to analyse the normal visuo-postural case. The eyes closed condition served to determine whether vision is important in the postural maintenance of the handstand. Comparison of the central dark condition and the normal condition was used to determine whether the gymnasts used central anchoring and to determine its importance. In the peripheral dark condition, we tested the influence of cue acquisition in the peripheral field, as described for central vision.

Several dependent variables were studied: the variance in the centre of pressure, which assessed the stability associated with the force variability in the handstand; the minima and maxima in the anterior-posterior and medio-lateral axes of the centre of pressure and the angles to account for movement in the handstand; the magnitude and variance of the angles (wrists, elbows, shoulders, and hips) to assess the postural organization; and the minima and maxima of the relative size of the gymnasts in the handstand [percentage of the size in handstand during the trials relative to the maximal size (=100%) in handstand measured before the tests; this size corresponded to the sum of the segment lengths] to provide information on movements in the vertical direction.

Statistical analysis

For the video data (angles and size), a Kolmogorov-Smirnov test revealed that the distributions did not satisfy the criteria of normality necessary for parametric tests. Thus, the median was used as an index of centrality and the Wilcoxon test for matched samples was used to compare the performances in the four experimental conditions. Since the results relative to the centre of pressure met all the criteria of normality, the data were analysed using analyses of variance to determine if there were interactions between the optical flows. When statistically significant effects were found ($P < 0.05$), Tukey's *post hoc* tests were used. To compare the minima and the maxima, we used Student's *t*-test. For all tests, statistical significance was set at $P < 0.05$.

Equations for the index of flow influence

Each of the four conditions represents a new state of adaptation. Regarding the analysis of the centre of pressure in the anterior-posterior and medio-lateral axes, an initial index was created to analyse the influence of central and peripheral flows compared with that of global vision in the handstand regulation. We assumed that the eyes open condition accounted for 100% of the relative stability (i.e. this was the condition in which the gymnasts used global vision and were the best adapted). This index was then calculated in the following way for peripheral vision (A). We measured the increase in variability observed in the absence of peripheral vision and then we expressed this relative to the state of variability in the eyes open condition:

$$\mathrm{A} = (\text{eyes open variance} - \text{central dark variance}) \times 100/\text{eyes open variance}$$

We followed the same procedure for central vision (B).

A second index based on the same principle measured the influence in the handstand regulation of central, peripheral, and global vision relative to the other balance systems. The eyes closed condition was the condition in which the gymnasts were assumed to use the other balance systems. The equation for central vision (E) was as follows:

$$\mathrm{E} = (\text{eyes closed variance - central dark variance}) \times 100/\text{eyes closed variance}$$

We followed the same procedure for peripheral (D) and global vision (C).

Results

Displacements in the centre of pressure

No significant differences among the four conditions were noted for the medio-lateral displacements.

Minima and maxima. Balance during the handstand in the normal condition was regulated primarily in the anterior-posterior axis, where the gymnasts held a maximal mean position (42.6 mm, $s = 8.4$) that was significantly more ahead ($t_9 = 27.5$; $P < 0.05$) of the minimal mean position (-35.2 mm, $s = 11.8$). There was thus an anterior-posterior displacement of significant magnitude during maintenance of the handstand in the normal condition. Moreover, this magnitude increased significantly in the eyes closed condition (eyes open: 77.8 mm, $s = 7.2$; eyes closed: 89.9 mm, $s = 6.0$) ($t_9 = 18.56$; $P < 0.05$).

Variance. The type of optical flow had a significant effect on the variance in the centre of pressure ($F_{6,34} = 7.95$; $P < 0.05$). More precisely, in the eyes open condition (mean 246.4, $s = 125.8$), the variance was significantly less ($P < 0.05$) than in the eyes closed condition (mean 470.0, $s = 162.8$) (Figure 2). The gymnasts thus held a significantly more stable handstand with normal vision than without vision. In

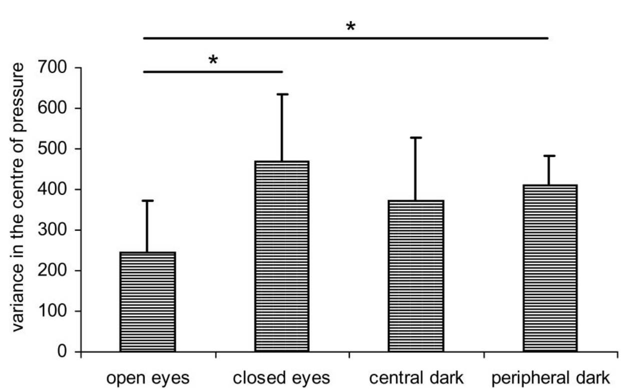

Figure 2. Variance in the centre of pressure on the anterior-posterior axis in the four experimental conditions.

addition, in the peripheral dark condition (mean 411.3, $s = 72.8$), the variance in the anterior-posterior axis of the centre of pressure was significantly greater ($P < 0.05$) than in the eyes open condition (mean 246.5, $s = 125.8$).

Video analysis

The gymnast's height. There was a significant difference ($t_{10} = 1$; $P < 0.05$) between the maximal median size of the gymnasts in the handstand (mean 99.4%, $s = 0.6$) and the minimal median size (mean 96.8%, $s = 1.1$). This mean variation in distance of 2.5% translates into a real deviation of about 4.5 cm in the vertical direction. In addition, the maximal size in the handstand was reached in the starting position and was never exceeded during the trials. The fluctuations occurred mainly between 97 and 99% of this length.

The magnitude and variance. The variances in the shoulder angle (mean 8.56°, $s = 1.5$) and wrist angle (mean 12.39°, $s = 1.8$) were significantly greater ($P < 0.05$) than those in the hip angle (mean 0.88°, $s = 0.5$) ($t_{10} = 1$ and $t_{10} = 0$, respectively) and elbow angle (mean 1.21°, $s = 0.5$) ($t_{10} = 1$ and $t_{10} = 0$, respectively) (Figure 3). Moreover, the very low variance in the hip and elbow angles indicated minimal movement, whereas a high variance was observed for the shoulder and wrist angles.

The magnitudes of displacement in the various angles specified the postural organization (Figure 4). The magnitudes of wrist angle (mean 15.14°, $s = 3.22$) and elbow angle (mean 13.63°, $s = 4.12$) displacement were significantly greater ($t_{10} = 0$ and $t_{10} = 3$, respectively; $P < 0.05$) than for the hip (mean 6.48°, $s = 2.10$). In addition, the magnitude of the wrist angle displacement was significantly greater ($t_{10} = 1$; $P < 0.05$) than that of the shoulder angle (mean 8.90°, $s = 3.58$).

Index of flow influence

The comparison of the variances revealed a peripheral flow influence of 50.7% in the anterior-posterior regulation compared with global vision. Central anchoring contributed 66.88% compared with global vision.

Compared with the other balance systems, vision was responsible for 47.56% of the handstand regulation. Peripheral vision contributed 12.49%, whereas central anchoring contributed 20.98%.

Discussion

The role of vision

The indices of flow influence and displacement revealed that the postural regulation of the gymnasts required more variations in the location of the applied forces to adapt their handstand balance without vision than with vision (Figure 2). Moreover, the participants were experienced gymnasts and we noted that, even though vision was not strictly necessary to maintain the handstand (they maintained the posture even with eyes closed), it played a significant role in their ability to balance, as noted for erect posture in the Romberg test. Vision ensures optimal postural adaptation.

Role of central anchoring

Because vision is useful for handstand maintenance, it is necessary to define the respective roles of peripheral and central vision in the detection of optical flow in this posture. First, perception of one's own movement is easier with central vision (Warren & Hannon, 1988), which explains the influence of central anchoring in handstand regulation. The loss of central anchoring indicated by the peripheral variance (peripheral dark condition) resulted in a significant increase in action (Figure 2).

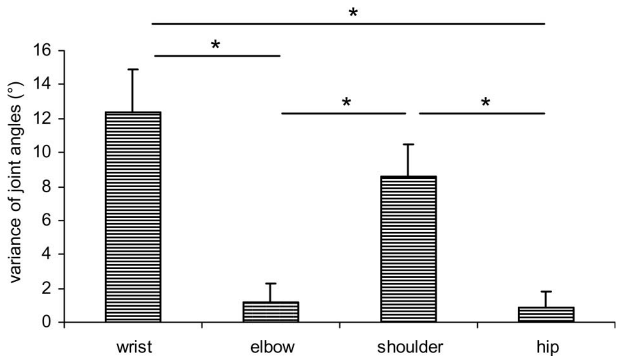

Figure 3. Variance of angles in the normal vision condition.

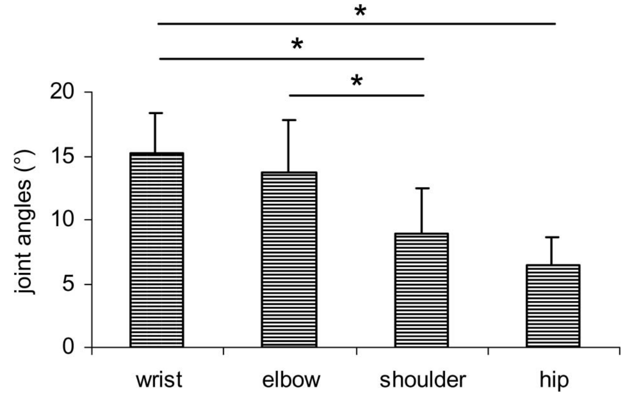

Figure 4. Magnitudes of displacements of angles in the normal vision condition.

Intra-modality and inter-modality of optical flow

According to our calculations, the relevant information that was picked up in peripheral vision and used for the anterior-posterior regulation of the handstand amounted to 50.7%, in comparison with global vision. The information provided by central anchoring amounted to 66.88%. The obvious question is how the sum of these two contributions exceeded the theoretical 100% of global vision.

One explanation is that a part of the local flow in central vision was also picked up by the peripheral system, which would confirm the proposition of Habak *et al.* (2002). In addition to this simple visual covering, a sensory inter-modality (Simoneau, Ulbrecht, Derr, & Cavanagh, 1995; Stoffregen & Bardy, 2001) could have been operating, or even a visual intra-modality. Indeed, the central and peripheral systems are not two distinct systems, and having central and peripheral information at the same time is a source of information in itself. In the central dark and peripheral dark conditions, the gymnasts may thus have lost part of their intra-modal information (in the optical flow) and their sensory inter-modality (between the optical flow and the other balance systems). In our comparisons of each visual system with global vision, we removed one of the inter- and intra-modal sources of information that contribute to the initial efficiency of the postural regulation, once for central vision and once for peripheral vision. The excess above 100% (17.58%) thus corresponded to the loss of redundancy of the intra- and inter-modalities due to the method adopted (grey area in Figure 5).

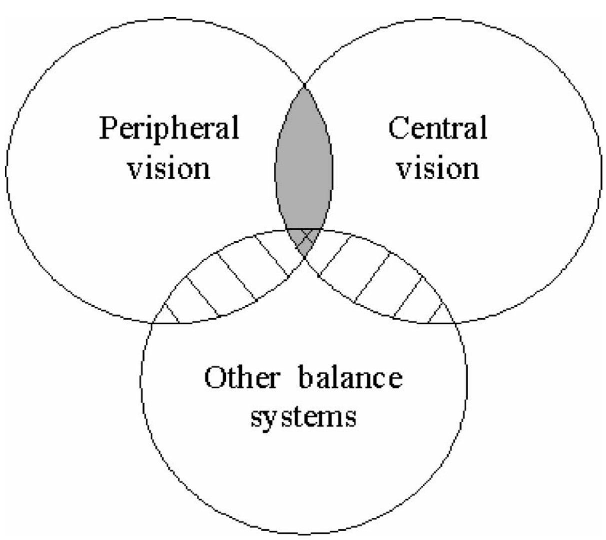

Figure 5. Theoretical representation of the visual intra-modality (grey area) and the sensory inter-modality (striped areas) of the different flows involved in handstand maintenance.

In addition, the relevant peripheral flow information used in the anterior-posterior control influenced 12.49% of the postural regulation in comparison with the theoretical 100% influence of all balance systems. The optical flow obtained by central anchoring accounted for 20.98%. The combination of these two local flows contributed 33.48%. However, the global vision flow was responsible for 47.56% of the anterior-posterior handstand control. This indicates that the visual system was the main source (about half) of the handstand regulation, in comparison with the other balance systems. The difference between these last two results (i.e. between 33.48% and 47.56%) can be explained by the intra-modal and inter-modal links between flows (grey area in the Figure 5) that occurred during global vision, which accounted for 14.09% of the postural regulation activity.

Towards a sensory multi-modality explanation of stability

Although central anchoring and peripheral vision are both important, a third factor thus emerges as essential: the link between the two flows obtained in global vision. Furthermore, the links between the different flows (central, peripheral, global vision, and the other balance systems) suggest that postural regulation is dependent on a multi-modality sensory organization (Simoneau *et al.*, 1995; Stoffregen & Bardy, 2001). The sensory organization that contributes to postural control is thus not summative, but is instead amplified by another sensory system associated with a specific flow. And in addition to the intra-modal covering that occurs in vision, these results point to inter-modal covering through the energies produced by the various flows (Figure 5). There is an emergent sensory phenomenon in the postural regulation.

Invariants

The principal displacements in the handstand occurred in the anterior-posterior and vertical planes. The visual flows that were created were thus, respectively and preferentially, lamellar and radial. For radial flow, the optical invariant that resulted was the focus of expansion (Bardy *et al.*, 1999; Stoffregen *et al.*, 1999). However, since handstand balance was controlled in the anterior-posterior axis, the vertical fluctuations could have been reflections of postural strategies rather than means of creating an optical flow containing information to regulate handstand maintenance. With lamellar flow, the gymnasts obtained optical information due in particular to the motion parallax. The gymnasts were able to detect the movement of their arms compared with their fixed environment, as well as the placement of their eyes (the head in hyperextension does not move) compared with central anchoring. The importance of the placement of the eyes compared with this central anchoring confirmed the findings of Clement and Rezette (1985). It corresponds to a relevant source of information in the handstand perceptual-motor task.

Ocular organization

The visual system contributed to the identification of displacements and the determination of whether the gymnasts were moving forwards or backwards. The system also provided information on the relative speed of the displacements, which aided decisions as to which postural strategies were best adapted to maintain equilibrium. The handstand was thus primarily controlled by a lamellate flow relative to the head position and the anterior-posterior displacement. Stoffregen *et al.* (1999) stated that ocular adjustments make it possible to stabilize erect posture in the lateral plane, whereas postural adjustments stabilize it in the anterior-posterior plane. However, eye placement, particularly with regard to central anchoring, is fundamental for the ocular organization that controls balance in the anterior-posterior plane of the handstand (Clement & Rezette, 1985; Clement *et al.*, 1988). In addition, Lee and Lishman (1975) showed that the closer the visual target is, the more the anterior-posterior oscillations decrease. Since the visual environment is closer in the handstand than in erect posture because of the head's proximity to the ground, the handstand should be better controlled visually than the upright posture, but this is not the case (Clement *et al.*, 1988; Kerwin & Trewartha, 2001; Slobounov & Newell, 1996). Although the optical situation perhaps favours the decrease in postural oscillations, the complexity of this unusual posture prevails and certainly requires more oscillations to produce optimal postural efficiency.

Postural organization

Three levels of organization. Nashner and McCollum (1985) described the organization of erect posture and highlighted a hierarchy of strategies that starts with the use of the ankle, then the hip and, finally, for important deviations, the knees. However, Asseman, Caron, and Crémieux (2003) determined that there is no transfer of postural ability from specific (handstand) to unspecific postures (upright posture) in elite gymnasts. Indeed, the maintenance of handstand posture appears more complex because it requires the participation of four instead of three joints: wrists, elbows, shoulders, and hips. Our results, however, showed that the shoulder and wrist movements varied considerably (Figure 3), the elbows did not vary very much (Figure 3) but did so with great magnitude (Figure 4), and the hips hardly moved (Figures 3 and 4). The gymnasts implemented a strategy that involved three joints. This idea is consistent with Bernstein's (1967) theory regarding the reduction in the degrees of freedom. To maintain this unusual posture, the gymnasts used the same strategy as in erect posture. This assumes the possibility of a constant postural organization or one that is limited to three levels.

An emerging hierarchy. The wrists showed important fluctuations. These fluctuations were vital because the orientation of the entire body depended on them (Kerwin & Trewartha, 2001). The shoulder movements participated to a lesser extent; however, their fluctuations offered additional postural flexibility. Finally, the inflection of the elbows allowed the gymnasts to quickly lower the centre of gravity in the event of extreme imbalance (like the knees in upright posture) and to obtain a greater tolerance margin in order to recover the handstand balance (Figure 4). The configuration is thus similar to that of erect posture, with the wrists functioning like the ankles, the elbows like the knees, and the shoulders equivalent to the hips. One might hypothesize that a transfer of postural control capacity occurs between the lower and upper limbs. Moreover, with reference to the study of Bardy *et al.* (1999), it might be more relevant to consider the modes of coordination emerging in a selective way instead of a postural hierarchy. With a flow informing the gymnasts about light displacement, the adapted postural reaction corresponded to an action of the wrists. For more significant balance variation, the shoulders assisted the actions already performed by the wrists.

Vertical regulation. In addition to the movements organized in the anterior-posterior plane (Kerwin & Trewartha, 2001; Slobounov & Newell, 1996), we observed displacements in the vertical plane. The objective of these movements was to raise the centre of gravity owing to an adduction of the wrists and a push of the shoulders upwards. The wrists thus had the major anti-gravity role. Moreover, the gymnasts never achieved their initial size in the vertical direction of the handstand. By keeping a margin in their alignment, the gymnasts obtained the additional flexibility necessary for the strategies of postural regulation that ensure handstand balance.

Postural regulation

According to Riccio and Stoffregen (1988), posture is regulated in a robust control zone and an adaptive control zone established around it. The role of this adaptive control zone is to acquire more information from a larger sensory flow than that present in the first control zone. With this additional information, new and more efficient postural strategies can be worked out. The differences in postural regulation observed in the four conditions of our study illustrate this point. Indeed, the flows were more or less available, depending on condition (central, peripheral, and with or without vision), and this generated different types of regulation that corresponded to different adaptive control zones. Moreover, each postural attitude corresponds to a sensory multimodality that specifies the participant/environment state necessary for the postural regulation, called the "global array" (Stoffregen & Bardy, 2001). Management of the intra- and inter-modalities discussed above and success in identifying the multi-modal characteristics of the limits of each zone seem to be fundamental to the acquisition and regulation of the posture.

References

Asseman, F., Caron, O., & Crémieux, J. (2004). Is there a transfer of postural ability from specific to unspecific postures in elite gymnasts? *Neuroscience Letters*, *358*, 83–86.

Asseman, F., & Gahéry, Y. (2005). Effect of head position and visual condition on balance control in inverted stance. *Neuroscience Letters*, *375*, 134–137.

Balasubramaniam, R., Riley, M. A., & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait and Posture*, *11*, 12–24.

Bardy, B. G., Warren, W. H., & Kay, B. A. (1996). Motion parallax is used to control postural sway during walking. *Experimental Brain Research*, *111*, 271–282.

Bardy, B. G., Warren, W. H., & Kay, B. A. (1999). The role of central and peripheral vision in postural control during walking. *Perception and Psychophysics*, *61*, 1356–1368.

Bernstein, N. A. (1967). *The coordination and regulation of movements.* Oxford: Pergamon Press.

Clement, G., Pozzo, T., & Berthoz, A. (1988). Contribution of eye positioning to control of the upside-down standing posture. *Experimental Brain Research*, *73*, 569–576.

Clement, G., & Rezette, D. (1985). Motor behavior underlying the control of an upside-down vertical posture. *Experimental Brain Research*, *59*, 478–484.

Edwards, A. S. (1946). Body sway and vision. *Journal of Experimental Psychology*, *36*, 526–535.

Gibson, J. J. (1966). *The sense considered as perceptual system.* Boston, MA: Houghton Mifflin.

Guerraz, M., Thilo, K. V., Bronstein, A. M., & Gresty, M. A. (2001). Influence of action and expectation on visual control of posture. *Cognitive Brain Research*, *11*, 259–266.

Habak, C., Casanova, C., & Faubert, J. (2002). Central and peripheral interactions in the perception of optic flow. *Vision Research*, *42*, 28–43.

Kerwin, D. G., & Trewartha, G. (2001). Strategies for maintaining a handstand in the anterior–posterior direction. *Medicine and Science in Sports and Exercise*, *33*, 1182–1188.

Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, *1*, 87–95.

Li, L., & Warren, W. H. (2000). Perception of heading during rotation: Sufficiency of dense motion parallax and reference objects. *Vision Research*, *40*, 3873–3894.

Li, L., & Warren, W. H. (2002). Retinal flow is sufficient for steering during observer rotation. *Psychological Science*, *13*, 485–491.

Marin, L., Bardy, B. G., Baumberger, B., Fluckiger, M., & Stoffregen, T. A. (1999). Interaction between task demands and surface properties in the control of goal-oriented stance. *Human Movement Science*, *18*, 31–47.

Marin, L., Bardy, B. G., & Bootsma, R. J. (1999). Level of gymnastic skill as an intrinsic constraint on postural coordination. *Journal of Sports Sciences*, *17*, 615–626.

Nashner, L. M., & McCollum, G. (1985). The organisation of human postural movements: A formal basis and experimental synthesis. *Behavioral and Brain Sciences*, *8*, 135–172.

Oullier, O., Bardy, B. G., Stoffregen, T. A., & Bootsma, R. J. (2002). Postural coordination in looking and tracking tasks. *Human Movement Science*, *21*, 147–167.

Redfern, M. S., Yardley, L., & Bronstein, A. M. (2001). Visual influences on balance. *Journal of Anxiety Disorders*, *15*, 81–94.

Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human Movement Science*, *7*, 265–300.

Simoneau, G. G., Ulbrecht, J. S., Derr, J. A., & Cavanagh, P. R. (1995). Role of somatosensory input in the control of human posture. *Gait and Posture*, *3*, 115–122.

Slobounov, S. M., & Newell, K. M. (1996). Postural dynamics in upright and inverted stances. *Journal of Applied Biomechanics*, *12*, 185–196.

Stoffregen, T. A. (1985). Flow structure versus retinal location in the optical control of stance. *Journal of Experimental Psychology*, *11*, 554–565.

Stoffregen, T. A. (1986). The role of optical velocity in the control of stance. *Perception and Psychophysics*, *39*, 355–360.

Stoffregen, T. A., & Bardy, B. G. (2001). On specification and the senses. *Behavioural Brain Science*, *24*, 195–213.

Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science*, *19*, 203–220.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilisation of looking. *Journal of Experimental Psychology*, *25*, 1641–1658.

Vuillerme, N., Nougier, V., & Prieur, J. M. (2001). Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? *Neuroscience Letters*, *308*, 103–106.

Warren, W. H., & Hannon, D. J. (1988). Direction of self-motion is perceived from optic flow. *Nature*, *336*, 583–585.

Warren, W. H., Kay, B. A., & Yilmaz, E. H. (1996). Visual control of posture during walking: Functional specificity. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 818–838.

Warren, W. H., & Kurtz, K. J. (1992). The role of central and peripheral vision in perceiving the direction of self-motion. *Perception and Psychophysics*, *51*, 443–454.