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Dynamics of expertise level: Coordination in handstand

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ABSTRACT

The aim of the present study was to investigate the effect of expertise on coordination patterns. We thus tested the coordination dynamics of two groups: experts in the handstand also having high expertise in gymnastics and experts in the handstand but only intermediate expertise in gymnastics. All participants were instructed to track a target with their ankles while maintaining the handstand. The target moved on the anterior-posterior axis according to three frequency conditions: 0.2, 0.4 and 0.6 Hz. The results showed that the suprapostural task was performed better by the group with high gymnastics expertise. Moreover, the spontaneous coordination was specific to the level of gymnastics expertise. We concluded that (i) the dynamics of coordination progress with the overall level of expertise in a sport discipline, independently of the mastery of a single skill, (ii) persistence and change are seen in related movement properties, and (iii) high expertise offers greater adaptability relative to the task.

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1. Introduction

According to the dynamical systems approach to the study of human movement, also known as coordination dynamics, postural control is an emergent phenomenon that results from the interaction of three types of constraint (Newell, 1986): task (e.g., instructions), environment (e.g., the support surface), and organism (e.g., age and body characteristics) (Bardy, Marin, Stoffregen, & Bootsma, 1999; Marin, Bardy, Baumberger, Fluckiger, & Stoffregen, 1999; Newell & McDonald, 1992). Perceptual-motor expertise is usually considered an organismic constraint because after years of practice of

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activities like surgery (Savoie et al., 2007) or particular sports (Bringoux, Marin, Nougier, Barraud, & Raphel, 2000; Marin, Bardy, & Bootsma, 1999; Vuillerme, Teasdale, & Nougier, 2001) the organism is changed entirely: muscular, perceptual, and psychological systems, to name a few, are different from what they were before practice. Given these findings, we suspect that perceptual-motor expertise also modifies the coordination dynamics in a particular way, just as physical maturation or body characteristics do. The expertise paradigm provides an interesting method to identify the effects of both motor learning and organismic properties on coordination dynamics. Moreover, expertise in a given sport is often defined in terms of a specific motor coordination, which may in turn modify the entire set of intrinsic organismic properties. The expertise paradigm is perhaps also most relevant for observing long-term changes because those changes are faster than maturational changes, less artificial than many experimental methods (e.g., adding mass to the body in order to change the height of the center of mass; Bardy et al., 1999), and less dramatic than studies based on body alterations (e.g., physical impairments). Last, the analysis of expertise yields information on the influence of both a constraint and its variations (i.e., level of expertise) on coordination dynamics. Previous work confirmed that expertise can be considered an organismic constraint by showing that expertise in gymnastics leads to functional modifications in postural coordination patterns (Marin et al., 1999). However, it remains unclear whether the level of expertise has direct consequences for postural coordination. In the present study we hypothesize that the level of the organismic constraint in general (operationalized here as level of expertise) influences postural coordination. The central question we addressed was whether changes in the level of a constraint automatically lead to alterations in postural coordination in general, and we expected that the findings of this study would help us to generalize to the two other types of constraint, i.e., task and environment.

Two paradigms have generally been used to characterize expertise, both through the investigation of a single skill, such as the handstand (Clement, Pozzo, & Berthoz, 1988) or tracking a target (Marin et al., 1999). In the first paradigm, novices and experts in a given sports are compared (Delignières, Nourrit, Deschamps, Lauriot, & Caillou, 1999; Temprado, Della-Grasta, Farrell, & Laurent, 1997), whereas in the second method, longitudinal studies examine the processes of skill acquisition. In studies of the latter type, the focus is on how novices learn a skill that is crucial to a specific sport (Delignières et al., 1998; Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003; Vereijken, van Emmerik, Whiting, & Newell, 1992). However, learning a skill does not imply becoming an expert in the sport that depends on it, as a sport requires many skills in interaction. A good example is gymnastics. As previously noted, we suspect that being an expert implies that the organismic properties have become entirely different from those of a novice. Thus, an individual with expertise in the global practice of a sport has a specific experience that should imply greater motor adaptability than would be seen in an individual who has mastered only a single skill of the sport in question (Abernethy, 1994; Ericsson & Lehmann, 1996; Starkes & Ericsson, 2003, for a review). In other words, we hypothesized that global practice experts would perform a specific skill differently than (novices that become) single skill experts.

Moreover, in the dynamical systems approach to motor learning typically three "stages of learning" are distinguished, characterized as freezing, releasing, and exploiting degrees of freedom (Bernstein, 1967; Berthier, Rosenstein, & Barto, 2005; Ivanchenko & Jacobs, 2003). Experts who are at the most advanced stage use all degrees of freedom to facilitate coordination. For these individuals, learning is a discontinuous process characterized by a qualitative reorganization of movement behavior in the course of practice (Newell, 1996). In such a context, we believe that when global practice experts are learning a new skill, they proceed through these three stages differently than non-experts. Consequently, we assume that even when the most advanced stage of motor learning of one skill is reached, having expertise in the practice of a sport should induce a specific mode of exploiting the degrees of freedom. In other words, the level of expertise in global practice should change the way individuals perform/exploit the degrees of freedom of a (previously controlled) specific skill.

Postural control is usually not an end in itself but subserves the achievement of suprapostural tasks (Stoffregen, Smart, Bardy, & Pagulayan, 1999). Postural studies typically show that the primary task in posture is maintaining the center of mass above its base of support, which is usually described as quiet stance. The quiet stance paradigm has produced a large body of literature. However, quiet stance may not be representative of ordinary posture (Stoffregen et al., 1999). Outside the laboratory, upright posture is rarely maintained for its own sake but instead facilitates the performance of suprapostural tasks (Riccio & Stoffregen, 1988; Smart, Mobley, Otten, Smith, & Amin, 2004; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Warren, Kay, & Yilmaz, 1996). Suprapostural tasks have been broadly used in "dynamical" and ecological postural coordination literatures for about two decades (e.g., Riccio & Stoffregen, 1988). Suprapostural tasks differ from the task of controlling posture in that they are defined and evaluated in different terms. The success or failure of a suprapostural task such as tracking a moving target with the head (Bardy et al., 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002) is not defined in terms of the position or motion of the body's center of mass. This and other parameters of postural motion can influence the performance of suprapostural tasks (e.g., excessive sway can degrade tracking), but task influences will be measured in different terms (e.g., perfect phase synchrony or similar amplitude between head and target). Thus, suprapostural tasks differ qualitatively from postural control (see Stoffregen et al., 1999, for further explanations and details about suprapostural tasks). The interest of this paradigm is to allow, without any behavioral instruction on the adopted coordination, the observation of the spontaneous emergent of postural coordination. Hence, rather than analyzing whether gymnasts, for instance, control quiet stance (i.e., sway less) better than non-gymnast athletes (Vuillerme, Danion et al., 2001), we investigated how these experts control suprapostural tasks (Marin et al., 1999). Within this framework, we assumed that experts in a global practice like gymnastics would display qualitative modifications in their postural coordination of a suprapostural task different from those of single skill experts. More generally, we predicted that the level of expertise (i.e., global expertise or single skill) would induce specific postural coordination when performing a suprapostural task.

Based on the paradigm of global practice expertise, we thus studied the consequences of the level of expertise constraint on suprapostural coordination. Although gymnastics is well known to modify organismic properties and to influence postural control (Bringoux et al., 2000; Marin et al., 1999; Vuillerme, Teasdale et al., 2001), we do not know whether the level of expertise leads to different postural coordination patterns in a specific skill. In this study, we investigated a specific gymnastic skill – the handstand while tracking a moving target – as an illustration of a complex suprapostural task. The handstand is a complex posture but adding another task to this posture greatly constrains the system. We predicted that a small change in this suprapostural task would have substantial consequences for balance and coordination, making it "easier" to assess the influence of level of expertise on such postural coordination.

Previous studies have presented the similarities between the handstand and erect posture; however, the joints involved in the control of these postures are different (Clement et al., 1988; Gautier, Thouvarecq, & Chollet, 2007; Kerwin & Trewartha, 2001; Slobounov & Newell, 1996). Although the coordination in erect posture is usually described in terms of the relative phase between the ankles and hips (Oullier, Marin, Stoffregen, Bootsma, & Bardy, 2006), three main joints seem to be used in the handstand: wrists, shoulders, and hips (Gautier et al., 2007; Kerwin & Trewartha, 2001; Slobounov & Newell, 1996). We thus analyzed the relatives phases between the angular movements of these three joints using the suprapostural task paradigm (i.e., a tracking task) (Bardy et al., 1999; Marin et al., 1999; Oullier, Bardy, Stoffregen, & Bootsma, 2002; Oullier et al., 2006). We expected to identify the spontaneous and emergent coordination adopted by gymnasts in the handstand posture. We further expected to demonstrate that the motor learning of one skill is not complete but is instead dependent on the level of expertise in the sport in which the skill is practiced. We specifically hypothesized that expert gymnasts would be able to perform a complex suprapostural task with greater success and display a different qualitative pattern of coordination in the handstand compared with gymnasts with a lower level of gymnastics expertise.

2. Methods

2.1. Participant

Sixteen male and female gymnasts were separated into two groups: a group of high-level experts (called high experts) and a group of intermediate experts (called low experts). All gave their informed consent to participate in the experiment. None had any visual or postural pathologies. All participants

Table 1
Means (standard errors) of the two experimental groups properties with their gymnastics (experience and competition level) and handstand (center of pressure and angular amplitudes) characteristics

	Low experts	High experts	Test *t*
Distribution	8	8	
	(Four women et four men)	(Three women et five men)	
Age (years)	21.10	22.30	0.40
	(3.50)	*(2.10)*	
Weight (kg)	63.58	65.55	0.24
	(5.87)	*(6.88)*	
Height (m)	1.61	1.66	0.86
	(0.07)	*(0.70)*	
Experience (years)	4.37	10.24	2.95*
	(1.83)	*(2.49)*	
Competition level	Regional/inter-regional	National/international	
COP surface (mm^2)	921.25	1037.87	0.62
	(533.86)	*(389.72)*	
A_{wrists} (°)	10.07	11.97	0.30
	(4.12)	*(2.81)*	
$A_{\text{shoulders}}$ (°)	7.25	8.95	0.27
	(3.01)	*(2.93)*	
A_{hips} (°)	16.07	12.44	0.18
	(5.87)	*(4.43)*	

COP, center of pressure and *A*, maximal amplitude in anterior–posterior.
* Inter-group significant difference ($p < .05$).

were able to maintain the handstand for 20 s or more and were handstand experts according to the international official rules of gymnastics (e.g., maintaining vertical body alignment on the hands without displacement for 2 s; FIG, 2006). Besides the usual official rules of gymnastics we have also provided more objective and quantitative handstand analyses. We analyzed the center of pressure (COP) displacements (surface) and the joint kinematics (wrist, shoulder, and hip amplitude) of a handstand performed without the tracking task for 20 s. Both the gymnastic referees' judgment and the objective (COP and kinematics) analyses revealed no significant inter-group differences in the handstand performance indicating that all participants had the same level of performance to maintain the handstand in quiet stance. Body, gymnastics experience, and handstand level characteristics (COP and kinematics) of the two groups are presented in Table 1.

2.2. Experimental device and design

The participants were asked to track the fore-aft displacements of a moving target with their ankles while they maintained the handstand on carry-hands. The target was a white circle (Ø = 1 cm) on a black background presented on a computer screen (size: 30.5 × 23 cm; resolution: 1024 × 768 pixels) placed on the ground between the carry-hands. The target oscillated between the participants' wrists with an amplitude of 5 cm. The display was generated with 3DSmax® software. Three frequency conditions were imposed: 0.2, 0.4, and 0.6 Hz. Due to the task difficulty, three trials per condition were performed. A trial was successful when the gymnast performed three oscillation cycles. The first cycle was not used for data analysis. Thus, for each participant, six cycles per condition were analyzed. Rest time and carry-hands width were freely determined by the participants and trials were performed in random order.

2.3. Data collection and analysis

Body movements in the fore-aft axis were recorded with a five-camera Vicon™ 512 infrared motion system at a sampling rate of 50 Hz and an accuracy of 1 mm. Six markers were fixed on the participants' right side: the middle finger of the right hand, the wrist, elbow, shoulder, hip, and ankle, to identify the coordination of the wrist, shoulder, and hip joint angles. Data samples were initiated and coordinated with a signal from the Vicon™ 512 system and the 3DSmax® display oscillation cycle so that the phase lag $\varphi_{\mathrm{rel(t-a)}}$ between the target (t) and the ankle (a) could be determined.

Task performance and postural coordination modes were analyzed.

Three dependent variables were used to analyze the suprapostural task performance. For each trial, the peak-to-peak amplitude A_{ankle} of ankle motion, the relative phase $\varphi_{\mathrm{rel(t-a)}}$ and the number of falls (failed trials) according to the three conditions were calculated. It was assumed that perfect performance of the task would produce an amplitude of 5 cm (the same amplitude as the target), with a relative phase of 0° and no falling.

To determine the postural coordination modes, the mean hip–wrist, hip–shoulder, and shoulder–wrist relative phases were calculated with phase subtraction. The wrist, shoulder, and hip phases were obtained from the point-estimate method, using one value per cycle (see Bardy et al. (1999) or Oullier et al. (2002) for a similar methodology on hip–ankle joints). The dependent variables were (i) the peak-to-peak angular amplitudes of the hip, shoulder, and wrist joints (A_{hip}, A_{shoulder}, and A_{wrist}), and (ii) the three relative phases determined by the relation between the hip (h) and shoulder (s) movements ($\varphi_{\mathrm{rel(h-s)}}$), between the hip and wrist (w) movements ($\varphi_{\mathrm{rel(h-w)}}$), and between the shoulder and wrist movements ($\varphi_{\mathrm{rel(s-w)}}$).

For performance, a two groups × three frequencies ANOVA with repeated measures on the second factor was applied to analyze the amplitudes and number of falls. When necessary, Newman–Keuls post-hoc tests were used. For the postural coordination modes, full circular statistics were applied since relative phases are considered circular variables (Batschelet, 1981). From the mean vector (r), we calculated the angular standard deviation to determine the relative phase homogeneity around the mean (Rayleigh's test). The modified Rayleigh test (V test) was also applied to determine whether coordination was significantly oriented toward an in-phase (0°) or an anti-phase (180°) mode. Watson–Williams tests were used to examine the influence of independent variables (groups and frequencies) on these circular variables. For all statistics, the significant threshold was $p < .05$.

3. Results

In general, all participants performed sinusoidal movements and succeeded in performing the suprapostural task. However, the tracking task performance and the observed coordination modes were different based on the level of expertise (Fig. 1).

3.1. Tracking performance

In general, the high experts performed the suprapostural task better than the low experts: (i) They fell less often than the low experts, (ii) followed the target with amplitudes close to the 5-cm target movement, and (iii) were more in-phase with the target (Table 2) than the low experts.

3.1.1. Failed trials

Concerning the number of failed trials, statistical analysis revealed a significant main effect of group, $F(1, 14) = 62.32$, and frequency, $F(2, 28) = 2.28$, but no interaction effect ($F(2, 28) = 2.05$). Whatever the condition, the low experts fell significantly more often than the high experts. Whatever the group, a higher number of failed trials was observed in the 0.2 and 0.6 Hz target frequency conditions than in the 0.4 Hz condition.

3.1.2. Amplitudes

In both groups, the anterior–posterior amplitudes of the ankles were greater than the 5-cm target oscillations. The ANOVA revealed significant group, $F(1, 14) = 30.07$, and frequency, $F(2, 28) = 5.23$, effects, but no interaction ($F(2, 28) = 0.06$) effect. The high experts oscillated with smaller ankle angular amplitudes than the low experts whatever the condition. The ankle angular amplitudes were smaller with a target frequency of 0.2 Hz than with the 0.4 and 0.6 Hz frequencies for both groups (see Table 2).

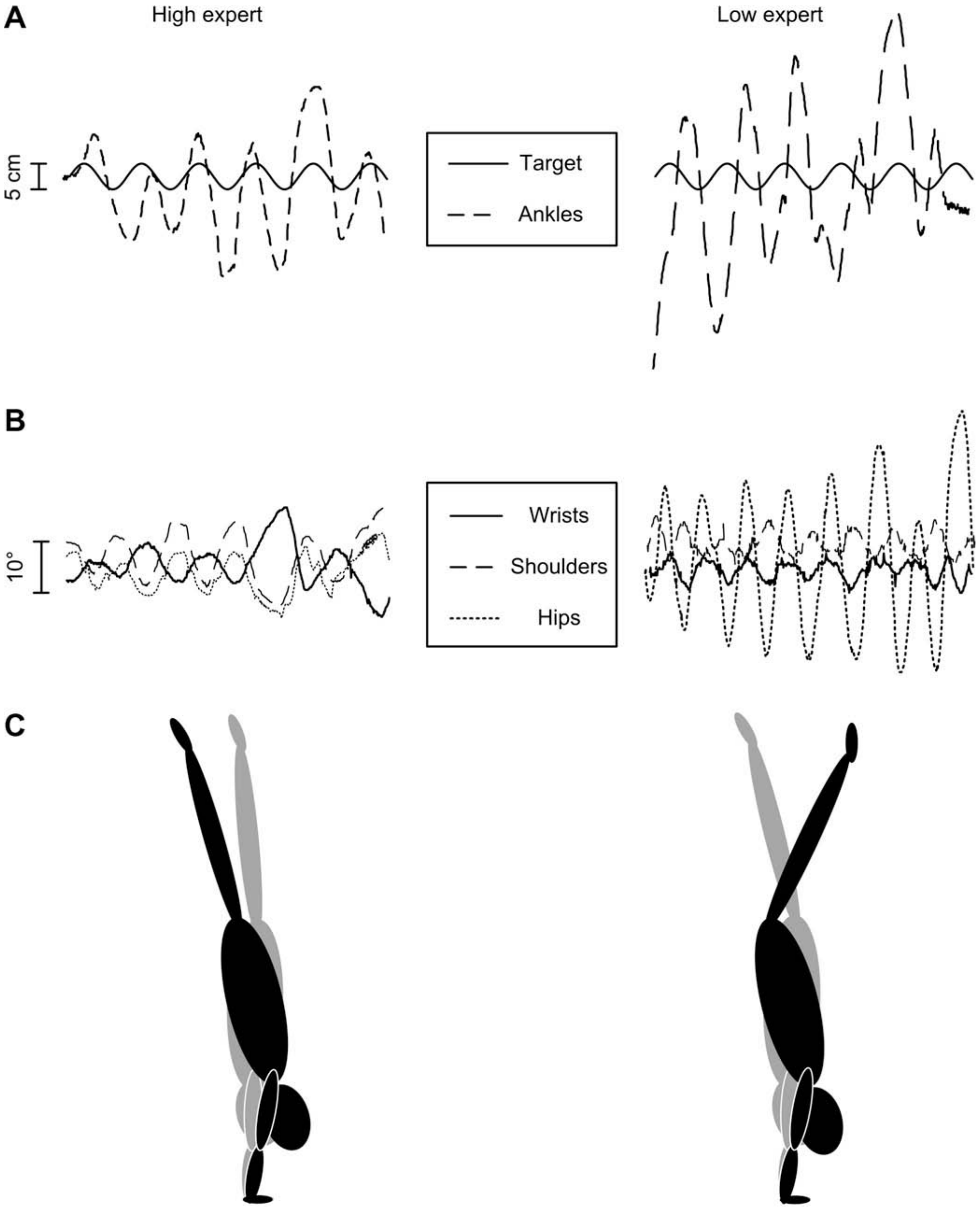

Fig. 1. Raw data representative of a high expert and a low expert for their ankle movements (A) and their angular movements (B) for six cycles with a 0.4 Hz target frequency with an illustration of the coordination adopted (C).

3.1.3. Relative phase

Circular statistics on the relative phase between the target and ankles showed that all means were significantly representative (*r* test), indicating that all observed behaviors were clustered around their respective means. Moreover, the high experts' ankle movements were significantly in-phase with the target oscillation ($p < .05$) in all conditions. Conversely, the phase lag of the low experts was too great to be in-phase with the target movement (*V* test). The Watson–Williams test revealed a significant ef-

Table 2
Means (standard errors) of the suprapostural task performances for the two groups according to the frequency conditions

Frequencies (Hz)	Groups	Failed trials	A_{ankle} (°)	$\varphi_{\text{rel(t-a)}}$ (°)	*r* test	*V* test
0.2	High experts	0.63 *(0.74)*	19.91 *(3.59)*	42.73 *(18.67)*	.95*	.70*
	Low experts	3.38 *(1.06)*	37.98 *(10.70)*	98.2 *(29.59)*	.87*	−.13
0.4	High experts	0.38 *(0.52)*	30.10 *(5.75)*	28.5 *(12.95)*	.98*	.86*
	Low experts	2.00 *(1.31)*	42.12 *(6.21)*	102.6 *(34.93)*	.83*	−.18
0.6	High experts	0.5 *(0.76)*	29.23 *(7.02)*	30.72 *(13.95)*	.97*	.84*
	Low experts	3.5 *(1.51)*	50.12 *(10.53)*	83.8 *(19.97)*	.94*	.1

A, amplitude and $\varphi_{\text{rel(t-a)}}$, relative phase between the target and the ankle.

* Data were significantly clustered around the mean (*r* test) or that relative phases were significantly oriented (*V* test) towards an in-phase mode (0°).

fect of group for all conditions. The high experts were significantly more in-phase with the target than the low experts with 0.2 Hz, $F(1, 14) = 17.63$, 0.4 Hz, $F(1, 14) = 27.08$, and 0.6 Hz, $F(1, 14) = 33.02$. Intercondition comparisons revealed no significant difference for the high experts ($F(1, 14) = 2.77$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 1.88$ for 0.2 vs. 0.6 Hz; $F(1, 14) = 0.09$ for 0.4 vs. 0.6 Hz) or the low experts ($F(1, 14) = 0.06$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 1.16$ for 0.2 vs. 0.6 Hz; $F(1, 14) = 1.56$ for 0.4 vs. 0.6 Hz).

3.2. Coordination patterns

3.2.1. Amplitudes

Amplitude and relative phase means are presented in Table 3.

3.2.1.1. Wrists. No significant effect appeared for the wrist angular amplitudes (group: $F(1, 14) = 1.02$; frequency: $F(2, 28) = 0.64$; interaction: $F(2, 28) = 0.98$).

Table 3
Means (standard errors) of the amplitudes (°) and relative phases (°) obtained from the hips, the shoulders and the wrists according to the group and the target frequency

Frequencies	Groups	A_{hip}	A_{shoulder}	A_{wrist}	$\varphi_{\text{rel(h-s)}}$	*r* test	*V* test	$\varphi_{\text{rel(h-w)}}$	*r* test	*V* test	$\varphi_{\text{rel(s-w)}}$	*r* test	*V* test
0.2 Hz	High experts	16.3 *(3.60)*	14.14 *(4.01)*	10.83 *(4.27)*	−18.92 *(9.28)*	.99*	.93*	−159.93 *(10.66)*	.98*	.92*	−178.07 *(6.71)*	.99*	.99*
	Low experts	28.68 *(6.60)*	7.91 *(1.95)*	7.56 *(2.78)*	153.87 *(16.78)*	.96*	.86*	25,35 *(27.96)*	.88*	.80*	−150.54 *(15.29)*	.96*	.84*
0.4 Hz	High experts	15.42 *(4.22)*	21.86 *(5.73)*	13.75 *(3.50)*	−14.32 *(8.09)*	.99*	.96*	−165,21 *(9.67)*	.98*	.95*	−179.48 *(7,.7)*	.99*	.99*
	Low experts	36.16 *(7.37)*	10.79 *(4.52)*	10.21 *(3.53)*	164.18 *(14.12)*	.97*	.93*	22,68 *(12.63)*	.97*	.90*	−150.76 *(17.96)*	.95*	.83*
0.6 Hz	High experts	11.66 *(2.30)*	25.87 *(5.88)*	15.15 *(5.60)*	−17.87 *(5.74)*	.99*	.95*	−165,53 *(8.85)*	.98*	.95*	−179.145 *(7.22)*	.99*	.99*
	Low experts	34.79 *(8.68)*	10.93 *(4.51)*	11.39 *(4.27)*	167.64 *(13.94)*	.97*	.95*	6,99 *(20.52)*	.93*	.93*	−163.50 *(11.48)*	.98*	.94*

r tests and *V* tests were presented on the right of the relative phase concerned.

A, amplitude; *h*, hips; *s*, shoulders; *w*, wrists and φ_{rel}, relative phase.

* Data were significantly clustered around the mean (*r* test) or that relative phases were significantly oriented (*V* test) towards an in-phase mode (0°).

3.2.1.2. Hips. For the hip angular amplitudes, ANOVA revealed a significant effect for the group condition, $F(1, 14) = 259.29$, whereas no effect was observed for frequency, $F(2, 28) = 1.09$, or interaction, $F(2, 28) = 2.88$. The high experts exhibited smaller hip angular amplitudes than those of low experts, whatever the condition.

3.2.1.3. Shoulders. For the shoulder angular amplitudes, significant effects of group, $F(1, 14) = 44.47$, frequency, $F(2, 28) = 14.08$, and interaction, $F(2, 28) = 4.65$, were observed. This last result indicated that, whatever the condition, the high experts moved their shoulders significantly more than the low experts. No significant difference was noted for the intra-group comparisons of the low experts. The high experts significantly increased their shoulder angular amplitudes when the frequency changed from 0.2 to 0.4 Hz and 0.2 to 0.6 Hz. However, no significant difference was observed between the 0.4 and 0.6 Hz conditions for this group. The interaction effect indicated that the higher the frequency and level of expertise were, the more the angular amplitudes of the shoulders increased.

3.2.2. Relative phases

For the relative phases, circular statistics showed that data were significantly clustered around their respective means (r test).

3.2.2.1. Relative phase between hip and shoulder $\varphi_{rel(h-s)}$. The results showed that the relative phase between hip and shoulder depended significantly on the group. Inter-group comparisons revealed a significant difference in all conditions, $F(1, 14) = 472.23$ for 0.2 Hz, 687.64 for 0.4 Hz, and 774.77 for 0.6 Hz, indicating that this relative phase had an important role in task performance. The high experts were significantly oriented toward an in-phase mode, whereas the low experts were oriented toward an anti-phase mode (V test). Moreover, the relative phases were negatively signed for the high experts and positively signed for the low experts. This last result indicated that coordination was led by the shoulders for the high experts and by the hips for the low experts. No significant difference appeared for the intra-group comparisons, neither for the high experts ($F(1, 14) = 0.98$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 0.06$ for 0.2 vs. 0.6 Hz and $F(1, 14) = 0.89$ for 0.4 vs. 0.6 Hz) nor for the low experts ($F(1, 14) = 1.56$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 2.81$ for 0.2 vs. 0.6 Hz, and $F(1, 14) = 0.21$ for 0.4 vs. 0.6 Hz).

3.2.2.2. Relative phase between hip and wrist $\varphi_{rel(h-w)}$. The hip–wrist relative phase was also significantly dependent on the group. Inter-group comparisons indicated a significant difference in all conditions, $F(1, 14) = 197.22$ for 0.2 Hz, 679.94 for 0.4 Hz, and 348.07 for 0.6 Hz. The results revealed that the high experts were significantly oriented toward an anti-phase mode, whereas the low experts significantly tended toward an in-phase mode (V test). As noted above, all relative phases were negatively signed for the high experts and positively signed for the low experts. This result indicated that the high experts led the hip–wrist coordination with their wrists and the low experts with their hips. No significant difference appeared for the intra-group comparisons, neither for the high experts ($F(1, 14) = 0.94$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 1.15$ for 0.2 vs. 0.6 Hz, and $F(1, 14) = 0.004$ for 0.4 vs. 0.6 Hz), nor for the low experts ($F(1, 14) = 0.05$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 1.99$ for 0.2 vs. 0.6 Hz, and $F(1, 14) = 3.00$ for 0.4 vs. 0.6 Hz).

3.2.2.3. Relative phase between shoulder and wrist $\varphi_{rel(s-w)}$. The results showed significant inter-group differences in all conditions, $F(1, 14) = 19.11$ for 0.2 Hz, 15.25 for 0.4 Hz, and 9.33 for 0.6 Hz). Both groups exhibited an anti-phase mode but the high experts significantly performed a coordination closer to a “perfect” anti-phase mode ((−)180°) than the low experts. Moreover, the two groups were significantly oriented toward a negatively signed anti-phase mode (V test). The wrists led the coordination for both groups. Finally, no significant intra-group effect was noted for the high experts ($F(1, 14) = 0.13$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 0.08$ for 0.2 vs. 0.6 Hz, and $F(1, 14) = 0.007$ for 0.4 vs. 0.6 Hz), nor for the low experts ($F(1, 14) = 0.006$ for 0.2 vs. 0.4 Hz; $F(1, 14) = 3.24$ for 0.2 vs. 0.6 Hz, and $F(1, 14) = 2.52$ for 0.4 vs. 0.6 Hz).

4. Discussion

The aim of this study was to determine the influence of level of expertise on postural dynamics. We specifically analyzed handstand coordination relative to expertise in gymnastics. The results are discussed in terms of performance and the coordination modes adopted by gymnasts across experimental conditions. The higher the level of expertise, the better the suprapostural task performance. Whatever the condition, each participant exhibited and conserved his or her own postural coordination mode, but, as illustrated in Fig. 1, participants used a different postural coordination mode according to their level of expertise.

4.1. Performance

First, the tracking performances revealed the difficulty of this suprapostural task for both groups. This was likely due to the high suprapostural constraints. In erect posture, non-homologous segments are solicited (Fourcade, Bardy, & Bonnet, 2003). In the handstand, the joints are also coupled (arms, trunk, and legs) and this coupling is a specific constraint on coordination. Moreover, in line with previous coordination dynamics studies, a supplementary constraint was imposed along with postural control to maintain dynamic balance (Oullier et al., 2006). These postural specificities had to be controlled in relation to the particular difficulty of performing an oscillated handstand (Gautier et al., 2007; Kerwin & Trewartha, 2001; Slobounov & Newell, 1996). The participants' imperfect performances suggested that an adaptive compromise was reached between maintaining balance as stable as possible and tracking a target, which was a potential cause of the loss of balance (Mitra, 2004). The management of such a complex posture limited performance and also required that the gymnasts adapted their coordination to successfully perform the suprapostural task (Riccio & Stoffregen, 1988; Stoffregen et al., 1999). For this reason, the performances seemed to be more degraded (for the low experts we even found that $\varphi_{\mathrm{rel(t-a)}}$ was never significantly in-phase) than the results observed in studies of erect posture (Bardy et al., 1999; Marin et al., 1999; Oullier et al., 2002, 2006). This comparison confirms the assumption that the more complex the posture is, the less success will be seen in performing the suprapostural task (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Mitra, 2003).

Nevertheless, regarding the number of falls, the 0.4 Hz frequency condition appeared to be an easier frequency for performing the suprapostural task than the 0.2 and 0.6 Hz conditions. In the literature on erect posture, target oscillation frequencies close to 0.2 and 0.6 Hz are known to impose severe constraints on a tracking task (Oullier et al., 2006). Thus, the spontaneous postural coordination in the handstand, as in erect posture, seemed to be preferentially organized around the same frequencies as the target oscillation. This suggests that these rhythms (close to 0.4 Hz) should be in line with the perceptual-motor characteristics of the human organism in a postural equilibrium. Moreover, a significant inter-group difference was observed for the failed trials. The low experts met with more difficulties than the high experts to adapt their behavior to the suprapostural task constraints. Analyses of expert performance in many domains reveal maximal adaptations of experts to domain-specific constraints (Abernethy, 1994; Ericsson & Lehmann, 1996). Then, our present results reveal that with their prior and important experience in gymnastics, high experts developed a greater adaptability in basic skill than low experts.

The analysis of tracking performance revealed better performance by the high experts. This quantitative inter-group difference was in line with the qualitative differences in the coordination adopted by each group. More particularly, the suprapostural task paradigm allowed the investigation of postural control with a situation in which coordination emerged without any instruction on the coordination to adopt. The present experiment therefore allowed us to determine both the emergent spontaneous coordination of the handstand and the influence of expertise on coordination. Significant divergences were observed in the postural synergies when the hips were considered.

4.2. Coordination modes

Although all participants met the criteria for performing the handstand (FIG, 2006 and Table 1), the two groups exhibited different coordination modes. Rather than revealing the ‘‘stage" (Bernstein, 1967; Newell, 1996) of handstand mastery, the inter-group difference was a reflection of overall expertise in gymnastics. Thus, the difference in the postural dynamics of the two groups strongly suggested that motor learning of one skill is not a complete and self-contained process on its own, but instead depends on the level of expertise in its related global practice.

The main difference concerned the hip movements. The low experts led their coordination with their hips ($\varphi_{\mathrm{rel(h-s)}}$ and $\varphi_{\mathrm{rel(h-w)}}$ were positive) with high angular amplitudes. A possible explanation is that the hips are the only joint that is common to both daily posture and handstand control. From this perspective, it seems that the low experts preferentially used the movement patterns usually devolved upon postural control. The high experts, on the other hand, mainly controlled their handstand with wrist–shoulder coupling. A distinguishing characteristic of the expert gymnast is a coordination pattern that conforms to the gymnastics rules which require, for instance, low angular movement of the hips (FIG, 2006; Marin et al., 1999). Thus, by adapting to the rules, experts can over time develop modified patterns of coordination even in situations where respecting the rules is not imposed.

The relative phase analysis revealed two main findings regarding the coordination patterns. On the one hand, each group adopted and conserved the same coordination for all the frequency conditions. Hence, the frequency shift had no effect on coordination. The difficulty of the task should have severely constrained the possibilities for action. This phenomenon has been regularly observed in coordination dynamics studies: the number of stable patterns seen decreases as the constraint level increases (Oullier et al., 2006; Zanone & Kelso, 1994). On the other hand, each group possessed its own coordination mode (Fig. 1). All the relative phases were significantly oriented toward an in-phase or an anti-phase mode, but the inter-group differences suggested that the high experts tended to be more synchronized (φ_{rel} close to 0° and 180°) than the low experts. Concerning the shoulder–wrist coordination, the same relative phase was computed for the two groups. The high and low experts were significantly oriented toward an anti-phase mode with a small advance of the wrists. However, the relative phase depended on the group when the hips were considered. The low experts led their coordination with their hips ($\varphi_{\mathrm{rel(h-s)}}$ and $\varphi_{\mathrm{rel(h-w)}}$ were positive) and the high experts with their shoulders and wrists ($\varphi_{\mathrm{rel(h-s)}}$ and $\varphi_{\mathrm{rel(h-w)}}$ were negative). Moreover, according to the group, the hips were oppositely coupled with the other joints. The hip–shoulder relative phase tended toward an in-phase mode for the high experts. The low experts adopted an anti-phase mode. Furthermore, our results for the angular amplitudes were in line with our findings for the relative phases. The angular amplitudes of the wrists were similar for the two groups but the high experts moved their hips less and their shoulders more for all conditions. In sum, the high experts mainly organized their coordination with shoulder–wrist coupling, whereas the low experts oscillated from their hips.

The two modes of coordination based on level of expertise were composed of both persistent and changing structures of movement. The same patterns were used for the shoulder–wrist coupling but the movement form changed when the hips were considered. According to previous studies, with learning, certain properties of movement forms and their outcomes persist over time, whereas others tend to change to allow better exploitation of the degrees of freedom (Bernstein, 1967; Berthier et al., 2005; Ivanchenko & Jacobs, 2003; Mégrot & Bardy, 2006; Newell, 1996). In the present study, the shoulder–wrist structure of movement persisted over the level of expertise while the coordination with the hips changed. Thus, for a motor skill like the handstand, this principle seems not to be limited to the last ‘‘stage of learning" of skill acquisition but to depend also on the expertise acquisition of the global practice. Furthermore, previous transfer studies reported that various micro-expertises (anticipation) could be transferred across macro-expertise (team ball sports) (Abernethy, Baker, & Côté, 2005; Smeeton, Ward, & Williams, 2004). However, in the present study, even in a micro-expertise (handstand), a transfer of functional coupling from a macro-expertise (gymnastics experience) seems to be operative and is not limited to a better or not quantitative performance, but leads to qualitative skill re-organizations. Nevertheless, the question of the nature of these transfer processes requires further investigation.

Moreover, actions are organized to both minimize energy expenditure and achieve task goals (Mark et al., 1997; Riccio & Stoffregen, 1988; Warren, 1984). This assumes that changes in coordination mode depend on the principle of efficiency. In our results, inter-group differences in coordination mode were observed in the same experimental conditions. This suggests the emergence of perceptual-motor efficiency, with specific impact on postural dynamics, according to level of expertise.

This study illustrates the merits of investigating expertise as a constraint on coordination dynamics. Although longitudinal study of the acquisition of a single skill (Delignières et al., 1998; Nourrit et al., 2003; Vereijken et al., 1992) and novice-expert comparisons (Delignières et al., 1999; Temprado et al., 1997) are useful to describe the phenomenon of expertise, our results underscore that the influences on coordination are specific to the level of expertise. The present experiment thus highlighted the importance of defining expertise as a constraint inherent to organisms because of its non-linear influence on motor behaviors. Modifications in properties pertaining to level of expertise are different from the modifications in external biomechanical constraints usually imposed on the participants of previous studies on coordination dynamics (e.g., adding mass or artificially changing foot length: Bardy et al., 1999; Marin et al., 1999). The expertise modifies the intrinsic organismic properties in such a way that the parameters of the spontaneous perceptive-motor patterns are re-defined.

To conclude, the present study indicated that expertise in a single motor skill continues to progress with experience in the broader activity in which the skill is implicated. Thus, skill acquisition and control are not ends in themselves. Ongoing practice of a skill and its interaction with other skills are able to re-define the exploitation of degrees of freedom. In particular, the differences observed concerned the adaptability required for new suprapostural task rather than skill performance. Moreover, the present study does not allow determining whether the level of expertise influences the learning of a new task. Questions such as these need to be addressed in future research.

References

Abernethy, B. (Ed.). (1994). Expert-novice differences in sport (special issue). *International Journal of Sport Psychology*, 25.

Abernethy, B., Baker, J., & Côté, J. (2005). Transfer of pattern recall skills may contribute to the development of sport expertise. *Applied Cognitive Psychology, 19*, 705–718.

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin, 58*, 135–139.

Bardy, B. G., Marin, L., Stoffregen, T. A., & Bootsma, R. J. (1999). Postural coordination modes considered as emergent phenomena. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1284–1301.

Bardy, B. G., Oullier, O., Bootsma, R. J., & Stoffregen, T. A. (2002). Dynamics of human postural transitions. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 499–514.

Batschelet, E. (1981). *Circular statistics in biology*. London: Academic Press.

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

Berthier, N. E., Rosenstein, M. T., & Barto, A. G. (2005). Approximate optimal control as a model for motor learning. *Psychological Review, 112*, 329–346.

Bringoux, L., Marin, L., Nougier, V., Barraud, P. A., & Raphel, C. (2000). Effects of gymnastics expertise on the perception of body orientation in the pitch dimension. *Journal of Vestibular Research, 10*, 251–258.

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.

Delignières, D., Nourrit, D., Deschamps, B., Lauriot, B., & Caillou, N. (1999). Effects of practice and task constraints on stiffness and friction functions in biological movements. *Human Movement Science, 18*, 769–793.

Delignières, D., Nourrit, D., Sioud, R., Leroyer, P., Zattara, M., & Micallef, J. P. (1998). Preferred coordination modes in the first steps of the learning of a complex gymnastics skill. *Human Movement Science, 17*, 221–241.

Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: Evidence of maximal adaptation to task constraints. *Annual Review of Psychology, 47*, 273–305.

FIG (2006). *Code of points*. Freiburg: FIG.

Fourcade, P., Bardy, B. G., & Bonnet, C. (2003). Modeling postural transitions in human posture. In S. Rogers & J. Effken (Eds.), *Studies in perception and action vii* (pp. 99–103). Hillsdale, NJ: Lawrence Erlbaum Associates.

Gautier, G., Thouvarecq, T., & Chollet, D. (2007). Visual and postural control of an arbitrary posture: The handstand. *Journal of Sports Science, 25*, 1271–1278.

Ivanchenko, V., & Jacobs, R. A. (2003). Developmental approach aids motor learning. *Neural Computation, 15*, 2051–2065.

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.

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 Science, 17*, 615–626.

Mark, L. S., Nemeth, K., Gardner, D., Dainoff, M. J., Paasche, J., Duffy, M., et al (1997). Postural dynamics and the preferred critical boundary for visually guided reaching. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1365–1379.

Mégrot, F., & Bardy, B. G. (2006). Changes in phase space during learning an unstable balance. *Neuroscience Letters, 402*, 17–21.

Mitra, S. (2003). Postural costs of suprapostural task load. *Human Movement Science, 22*, 253–270.

Mitra, S. (2004). Adaptive utilization of optical variables during postural and suprapostural dual-task performance: Comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). *Journal of Experimental Psychology: Human Perception and Performance, 30*, 28–38.

Newell, K. M. (1986). Constraints on the development of coordination. In M. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspect of coordination and control* (pp. 341–360). Dordrecht: Nijhoff.

Newell, K. M. (1996). Change in movement and skill: Learning, retention and transfer. In M. Latash & M. Turvey (Eds.), *Dexterity and its development* (pp. 393–429). Hillsdale, NJ: Lawrence Erlbaum Associates.

Newell, K. M., & McDonald, P. V. (1992). Searching for solutions to the coordination function: Learning as exploratory behavior. In G. E. Stelmach & J. Requin (Eds.), *Tutorial in motor behavior II* (pp. 517–532). Amsterdam: Elsevier Science.

Nourrit, D., Delignières, D., Caillou, N., Deschamps, T., & Lauriot, B. (2003). On discontinuities in motor learning: A longitudinal study of complex skill acquisition on a ski-simulator. *Journal of Motor Behavior, 35*, 151–170.

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.

Oullier, O., Marin, L., Stoffregen, T., Bootsma, R. J., & Bardy, B. G. (2006). Variability in coordination postural dynamics. In K. Davids, S. J. Bennett, & K. M. Newell (Eds.), *Movement system variability* (pp. 25–47). Champaign: Human Kinetics Publishers.

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

Savoie, S., Tanquay, S., Centomo, H., Beauchamp, G., Anidjar, M., & Prince, F. (2007). Postural control during laparoscopic surgical tasks. *American Journal of Surgery, 193*, 498–501.

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

Smart, J. L. J., Mobley, B. S., Otten, E. W., Smith, D. L., & Amin, M. R. (2004). Not just standing there: The use of postural coordination to aid visual tasks. *Human Movement Science, 22*, 769–780.

Smeeton, N. J., Ward, P., & Williams, A. M. (2004). Do pattern recognition skills transfer across sports? A preliminary analysis. *Journal of Sports Sciences, 22*, 205–213.

Starkes, J., & Ericsson, K. A. (2003). *Expert performance in sports: Advances in research on sport expertise*. Champaign, IL: Human Kinetics.

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: Human Perception and Performance, 25*, 1641–1658.

Temprado, J. J., Della-Grasta, M., Farrell, M., & Laurent, M. (1997). A novice-expert comparison of (intra-limb) coordination subserving the volleyball serve. *Human Movement Science, 16*, 653–676.

Vereijken, B., van Emmerik, R., Whiting, H. T. A., & Newell, K. M. (1992). Freezing degrees of freedom in skill acquisition. *Journal of Motor Behavior, 24*, 133–142.

Vuillerme, N., Danion, F., Marin, L., Boyadjian, A., Prieur, J. M., Weise, I., et al (2001). The effect of expertise in gymnastics on postural control. *Neuroscience Letters, 303*, 83–86.

Vuillerme, N., Teasdale, N., & Nougier, V. (2001). The effect of expertise in gymnastics on proprioceptive sensory integration in human subjects. *Neuroscience Letters, 311*, 73–76.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 683–703.

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.

Zanone, P. G., & Kelso, J. A. S. (1994). The coordination dynamics of learning: Theoretical structure and experimental agenda. In S. P. Swinnen & H. Heuer (Eds.), *Interlimb coordination: Neural, dynamical, and cognitive constraints* (pp. 461–490). San Diego, CA: Academic Press.