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Postural organisation during cascade juggling: Influence of expertise

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Abstract

The present study investigated how posture is organised during three-ball cascade juggling according to expertise. We hypothesized that the juggling task would place constraints on the postural organisation mode and that the posture–juggling coupling would be increased with expertise. Two groups, intermediates and experts, were asked to perform a postural-cascade juggling task. A three-dimensional motion recording system recorded the position of five light-reflecting markers for 30 s to analyse the ball movements, the lateral oscillations of the sacrum and the flexion/extension of the right elbow. The spatial pattern of the cascade juggling showed no significant difference between groups. Moreover, both groups presented lateral oscillations of the sacrum during the task. The latencies between the maximal flexion/extension of the right elbow and the maximal lateral oscillations of the sacrum and their standard deviations were significantly lower for the experts than for the intermediates. We conclude that postural adaptations occur to facilitate the postural–suprapostural task and that experience modifies the posture–juggling coupling.

Keywords: Posture; Cascade juggling; Facilitation; Variability; APA

1. Introduction

Juggling displays rich sensorimotor dynamics for investigating the temporal and spatial constraints of hand and ball motions [1–4]. Juggling is keeping several objects, such as balls, simultaneously in motion in the air by tossing and catching. The cascade is generally the first juggling skill a person learns. In cascade juggling, one hand moves clockwise and the other anti-clockwise with an average phase difference of about 180°. In this particular pattern, the balls are released at the inside of the ellipses and caught at the outside. Between throws and catches, they travel through the air to the other hand along a parabolic trajectory. The three-ball cascade reflects a figure-8 pattern rotated by 90° (Fig. 1). One hand tosses or unloads the object in such a manner that the ball is thrown in a parabolic arc at about eye level towards the other hand. The second ball is tossed just prior to catching the first ball with its parabolic arc corresponding to the opposite shoulder. In the course of a full revolution of a ball to its original position, the ball travels once from left to right and *vice versa* as it travels twice along its parabolic flight path. Furthermore, the balls are juggled equidistantly in time, which can be viewed as phase locking between the balls. Each ball must be thrown sufficiently high to allow the juggler time to deal with the other balls. van Santvoord and Beek [5] thus proposed that the cascade juggling pattern is comparable to a spatial clock.

In sports in which the performers have to master the execution of closed skills in codified patterns (such as cascade juggling), stability seems to be more important than variability [6–8]. Elite athletes thus repeat the basic techniques of a sport better and more efficiently than less experienced athletes [7–9]. For this reason, the repeatability

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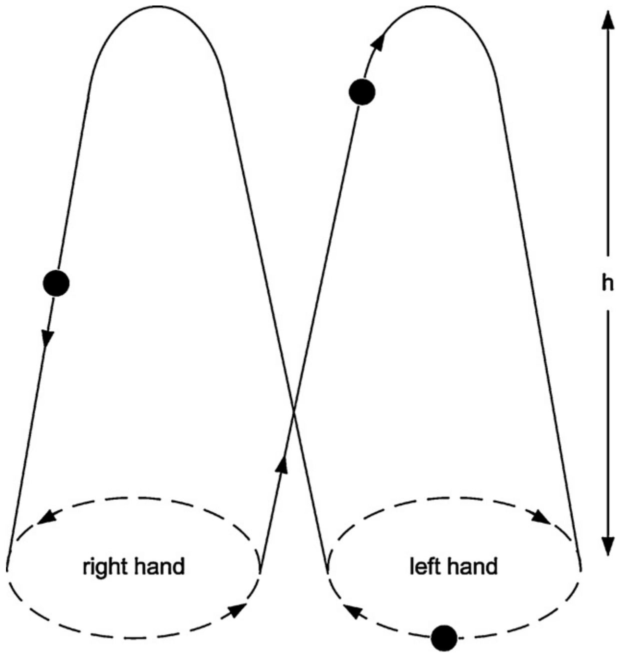

Fig. 1. Schematic representation of juggling with three balls in a height-figure pattern (cascade juggling). *h* corresponds to the vertical displacement of the balls.

of a specific technique is currently accepted as a valuable indicator of the performer's skill. Nevertheless, variability, which is not only spatial but also temporal, should be viewed as an intrinsic and essential property of human movement systems and may be exploited to obtain vital information about the control structure of these systems [10]. This feature is general to movement in action [11] and intrinsic to the cascade juggling motions [4]. The hands must be coordinated so that a spatial–temporal pattern to the ball motions is established over the full juggling cycle. The hands alternately toss and catch the balls, nearing an antiphase relation [1,2].

Juggling also implies postural coordination, which to our knowledge has never been focused on apart from learning [12,13]. This coordination has postural stabilisation as the main goal during the task. Riccio and Stoffregen [14] argued that postural stabilisation is not an end in itself but is valuable only to the extent that it facilitates the achievement of other goals. Stance can be controlled in different ways which will differentially impact the success of other behaviours. From this perspective, the success of postural control actions is defined in terms of their impact on the achievement of suprapostural goals [15]. Several types of research suggest that the control of posture may be modulated adaptively so as to facilitate suprapostural activity [14,16–19].

According to Saini et al. [20] and Thirunarayan et al. [21], the displacement of the centre of mass can be assessed from the displacement of the spinous process of S1 during an upright movement. During upright juggling, ball catching and throwing from one hand to the other requires the alternating extension and flexion of the elbow. Thus, a marker applied on the sacrum cannot be assumed to be the centre of mass. However, Giese et al. [22] suggested that ‘‘posture may relate to other movement tasks by stabilization against the mechanical perturbations induced by such movements.’’ Therefore, ball catching in one hand (right or left) should be counterbalanced by a lateral displacement of the sacrum to the other side during the juggling spatial clock [5].

The purpose of this study was to test this latter hypothesis, as well as the hypothesis that postural facilitation is different in experts and intermediate jugglers.

2. Methods

2.1. Subjects

Five expert jugglers and five intermediate jugglers participated in the experiment. Expert jugglers were defined as those who could juggle five or more balls. Intermediate jugglers were defined as those who could comfortably maintain a three-ball juggle for more than a minute [23]. All subjects were right-handed and had normal or corrected-to-normal vision. The subjects' morphological characteristics (Table 1) showed no difference between the two groups (non-parametric Mann–Whitney *U*-test). However, the experts' mean experience in juggling was significantly higher than that of the intermediates (Table 1). Before participating in this study, the jugglers were fully informed about the protocol and gave written consent according to the procedure approved by the University ethics committee.

2.2. Materials

The subjects were asked to perform a standard three-ball cascade juggling task for at least 30 s. No information about the tempo was given (spontaneous tempo). All juggles were performed with three plastic ‘stage balls' with a diameter of 7.3 cm and a mass of 130 g. Each subject was recorded twice; the first recording was used to familiarise the athletes with the balls and markers. These initial data were not used. All tests were carried out in the Rouen Laboratory of the Research Group on Gait Disorders (GRHAL). A three-dimensional motion recording system (Vicon 512^{TM}, Oxford Metrics Ltd., Oxford, UK) recorded the position of five light-reflecting markers (Ø25.4 mm) fixed with double-faced adhesive tape, with five cameras at the sample rate of 50 Hz. The markers were applied to the following anatomical sites: the seventh cervical vertebra, the right lateral epicondyle (elbow), the palmer side of the carpus (wrist), the lateral edge of the acromion (shoulder) and the spinous process of S1 (sacrum). As the subjects were jugglers, the three balls were juggled equidistantly in time. Adhesive reflective tape was thus applied on only one of the three juggling balls. The three-dimensional trajectories of the markers were smoothed using Fourier transforms with a cut-off frequency at 10 Hz. After smoothing, the accuracy of this motion recording system was estimated at 0.01° for the angle and 0.05 mm for the trajectory measurement in an acquisition volume of 3 m^3. For each juggling cycle, the number of frames was transformed into a percentage of the movement [8]. All the cycles were normalised, from the beginning (considered as time 0) to the end of the exercise ($t_{\max} = 100\%$). Zero percent (0%) corresponded to the minimal height of the ball in the right hand and

Table 1
Morphological characteristics and juggling experience of the two groups (mean ± S.D.)

Groups	Age (years)	Height (m)	Mass (kg)	Experience (years)
Experts (*n* = 5)	23.00 ± 3.32	1.76 ± 0.06	70.00 ± 6.78	8.00 ± 2.92
Intermediates (*n* = 5)	23.40 ± 2.30	1.78 ± 0.02	69.40 ± 6.66	1.80 ± 0.84
p value	0.59	0.60	0.92	0.009

100% corresponded to the following minimal height of the same ball in the same hand (Fig. 2a). The first three full juggling cycles were removed from all time series to eliminate possible transient effects associated with the start-up of the juggle. Ten cycles for each juggler were analysed.

The spatial variables (mean maximal height of the ball, mean amplitude of the elbow flexion/extension in the sagittal plane, mean amplitude of the sacrum's lateral oscillations in the frontal plane) were first characterised. The lateral sacral angular displacements are similar to those of a pendulum. These displacements were thus calculated as the sacrum linear lateral displacements relative to the seventh cervical vertebra considered as fixed and in the vertical axis. The temporal variable (mean ball cycle duration, mean interval of a cycle between the elbow flexion/extension and the maximal oscillation of the sacrum) was then characterised. This mean interval was expressed as a percentage of the cycle duration. A latency was established between, first, the maximal flexion of the right elbow and the maximal oscillation of the sacrum to the right (ball off the right hand: *Boff*) and, second, between the maximal extension of the right elbow and the maximal oscillation of the sacrum to the left (ball in the right hand: *Bin*). Since there was no video recording of the juggling task, we did not know exactly when the subjects caught and released the ball. However, because of the nature of the task, the ball is still in the hand at the maximal extension of the elbow and the ball has already been released at the maximum flexion of the elbow.

2.3. Statistical analysis

All data apart from anthropometric values met the criteria for distribution normality (Shapiro–Wilk test) and homogeneity of variance (Bartlett test) and allowed parametric statistics. Thus, to compare subjects' characteristics, the Mann–Whitney *U*-test was used. The ball cycle duration, the maximal height of the ball, the amplitude of the sacrum's lateral oscillation and the amplitude of the elbow flexion/extension were compared using an independent Student's *t*-test. The latencies between the maximal right elbow flexion/extension and the maximal lateral oscillation of the sacrum were assessed by a two-way ANOVA [Group (two levels: experts, intermediates) × Side (two levels: Boff, Bin)]. Last, a two-way ANOVA [Group (two levels: experts, intermediates) × Side (two levels: Boff, Bin)] was performed on the standard deviations of the latencies. When necessary, these ANOVAs were completed by post hoc HSD Tukey tests. For all analysis, the level of significance was set at $p < 0.05$.

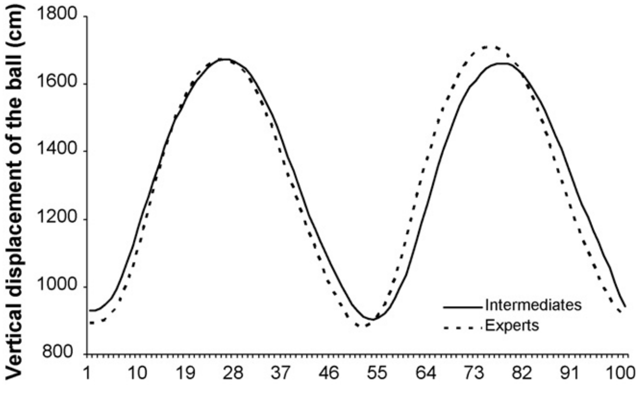

Fig. 2. Vertical ball displacement of experts and intermediates during a cascade cycle (cm).

3. Results

3.1. Spatial data

The mean maximal height of the ball (Fig. 2) was not significantly different between the experts (1700.36 ± 77.71 cm) and the intermediates (1684.05 ± 77.90 cm) ($t(187) = 1.44$; $p = 0.15$). The mean amplitude of the elbow flexion/extension was not significantly different between the experts (45.02 ± 16.06°) and the intermediates (43.71 ± 11.39°) with $t(198) = 0.62$ and $p = 0.53$. No difference was observed ($t(283) = 1.84$; $p = 0.06$) in the mean amplitude of the lateral oscillations of the sacrum between these two groups; respectively 1.70 ± 0.71° and 1.55 ± 0.69° for the experts and the intermediates (Fig. 3).

3.2. Temporal data

The Student's *t*-test failed to reveal a significant difference between the mean cycle duration of the experts (2.20 ± 0.18 s) and that of the intermediates (2.17 ± 0.13 s) with $t(88) = -0.73$ and $p = 0.47$.

The two-way analysis of the mean latencies (Boff and Bin) revealed a significant effect of Group ($F(1, 383) = 22.79$; $p = 2.58 \times 10^{-6}$). The latency was significantly lower for the experts (−5.32 ± 3.91%) than for the intermediates (−7.60 ± 5.95%). The maximal lateral oscillations of the sacrum according to the maximal flexion/extension of the right elbow thus occurred earlier in the experts than in the intermediates. Moreover, a significant interaction between Group and Side was observed ($F(1, 383) = 4.38$; $p = 0.037$). The post hoc HSD Tukey test underlined that the latencies of the intermediate jugglers (−8.06 ± 4.38%) were higher than those of the experts (−4.58 ± 3.02%) for the left side (Fig. 4).

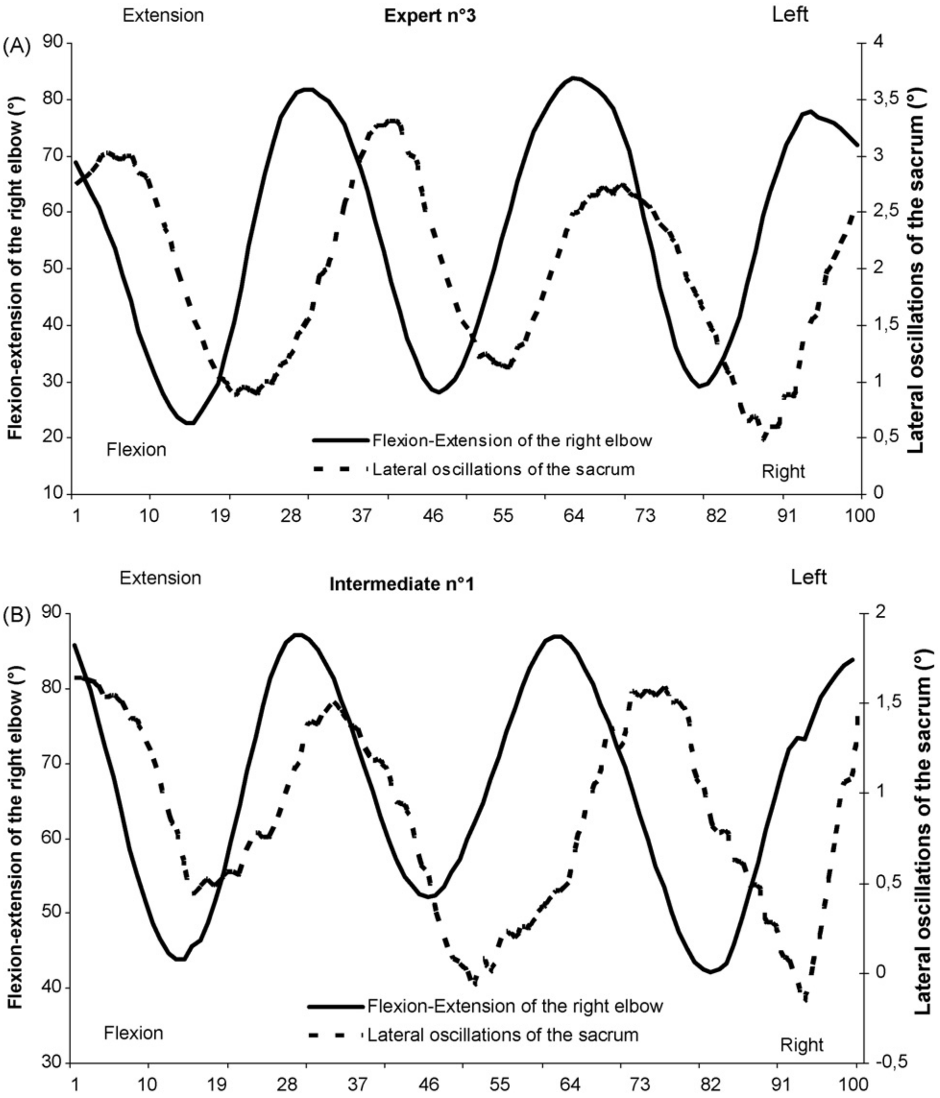

Fig. 3. Examples of flexion/extension of the right elbow (°) and lateral oscillations of the sacrum (°) in an expert (A) and an intermediate (B) subject during a cascade cycle.

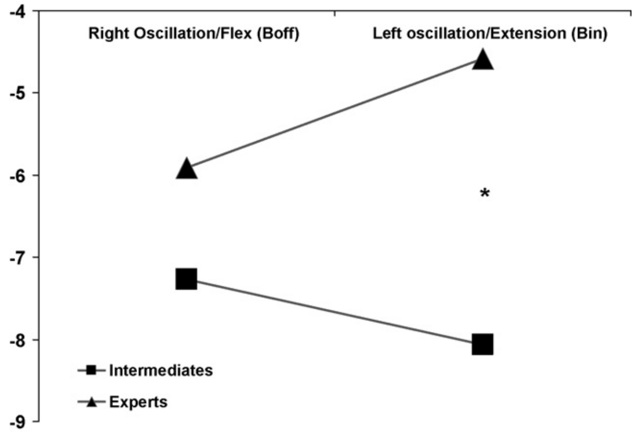

Fig. 4. Mean latencies between the maximal right and left oscillations of the sacrum and the maximal flexion and extension of the elbow (means of Boff and Bin) (% of a cycle) of experts and intermediates.

Last, the two-way analysis of the standard deviations of the latencies revealed a significant effect of Group ($F(1, 40) = 6.23$; $p = 0.017$). The intermediates presented higher standard deviations of the latencies than the experts (5.95% vs. 3.91%).

4. Discussion

Since both groups were able to juggle three balls, it was not surprising that the mean duration of a cycle, the flexion/extension of the elbow and the maximal vertical displacement of the ball were not significantly different. Their cascade juggling patterns thus seemed to be spatially similar. However, both groups also presented similar lateral oscillations of the sacrum. Although the hands alternately toss and catch the balls in cascade juggling, nearing an antiphase relation [1], this rhythmically changes the position of the centre of mass. In fact, the sacral displacements were systematically directed to the side opposite to the hand receiving the ball (Fig. 2). When the right hand was receiving the ball (extension of the elbow), the displacement of the sacral marker was towards the left side. Giese et al. [22] suggested that ''posture may relate to other movement tasks by stabilization against the mechanical perturbations induced by such movements.'' These sacral displacements thus indicted a minimisation of the displacement of the centre of mass during the cascade juggling. This thus confirmed our hypothesis that posture is organised around juggling and facilitates this task.

Moreover, both the mean latencies and their standard deviations were significantly lower for the experts than for the intermediates. In closed skills executed in codified patterns, stability is considered to be a valuable indicator [6–8] of performance. In agreement with these studies, the lower mean standard deviation of the experts thus indicated the more reproducible temporal postural organisation around the cascade juggling of these jugglers. As the latencies were significantly different, sacral stabilisations did not occur at the same time in the experts and intermediates. The experts showed an earlier initiation of the sacral movement to the opposite direction of the catching hand, or to the same direction as the throwing hand, than the intermediates. Vereijken et al. [24] observed experienced-based changes in coordination of the hips, ankles and knees in the context of an explicit suprapostural task (learning to ski). Bardy et al. [16] found that multisegmental postural control varied adaptively with changes in the amplitude of intentional head movements used to track a moving target. This suggests that the precision of postural stabilisation may be a function of the degree of stabilisation required for the performance of a given task. This, in turn, suggests that postural motion might differ across suprapostural tasks, with the differences being adaptively related to task-imposed constraints [14]. In agreement with these studies, our results appear to demonstrate that postural control actions can be varied adaptively to facilitate this suprapostural juggling activity. As the experts were able to juggle five balls or more, they had a more complex experience of juggling than the intermediates. This experience modified the posture–juggling coupling. According to Paillard [25], posture can be defined as the manner in which the organism faces stimulation from the external world and prepares itself to react to this stimulation. This function is assured by the postural adjustments made before, during and after the movement. These postural adjustments stabilise and maintain reference values in the face of perturbations arising within the subject itself or in external events [26]. They can be either reactive (RPA) or anticipatory (APA). In the first case, postural regulation is centred on the compensation of unexpected perturbations and thus results from sensory feedback. RPAs correct task-induced perturbations in order to restore the projection of the centre of gravity inside the sustentation polygon. In the second case, APAs correspond to dynamic phenomena which are centrally pre-programmed and appear progressively with experience [27]. These anticipatory activations engender dynamic forces whose direction is the opposite of that of the task-induced perturbations [28]. With regard to the role of posture in facilitating juggling, Latash et al. [29] suggested that APAs are based on predictions of postural perturbations that take into account the motor, environmental and cognitive contexts. APAs are thus parameterised according to the consequences of an action rather than to the action itself [30]. Our results indicated that APAs were present during the juggling task but that they differed with expertise. Both the regularity and stability of the postural organisation patterns of the experts suggested a better facilitation of the postural–suprapostural task. Moreover, both the significantly higher latencies and the standard deviation of the latencies of the intermediates indicated that the posture–juggling coupling would be more easily destabilised.

In summary, juggling is complex enough to have interesting properties and simple enough to allow the modelling of these properties. It involves not only a remarkable use of the hands but also complex spatial perception, cognitive skills and posture. It has proven to be a very useful experimental task for studying the dynamical properties of human perceptual-motor organisation [1–4]. In our study, posture organised around a juggling spatial clock and this facilitation differed according to expertise. Jugglers were able to juggle in a reproducible way with anticipatory postural adjustments of the sacrum. It thus would be interesting to study the coupling of posture with reverse cascade juggling, which is known to be more difficult than the standard cascade, or five-ball cascade juggling, taking into account the exact moment of the catching and releasing of the ball. Moreover, this posture–juggling coupling should be investigated in seated subjects with and without stabilised shoulders. In the first case, the shoulders should oscillate laterally instead of the sacrum. In the second case, intermediate jugglers may not succeed in the cascade task and the experts' cascade juggling should be more variable.

Conflict of interest statement

None.

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