

MOVEMENT REGULATION OF GYMNASTICS SKILLS UNDER VARYING ENVIRONMENTAL CONSTRAINTS

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ABSTRACT

Introduction: Gymnasts perform complex skills on stationary apparatuses. The perceived structure of each apparatus in relation to gymnasts' position, orientation and state of motion is one important factor that influences movement regulation. This study targeted the question, how gymnasts regulate complex skills as a function of varying apparatus constraints. **Materials and Methods:** Trained gymnasts performed three cartwheels in a row under two different experimental conditions of manipulated apparatus constraints (increased and decreased space available on a spring floor in order to perform the cartwheels). Gymnasts' regulation strategy in the different experimental conditions was assessed. **Results:** Results revealed that gymnasts perfectly accommodated the manipulated apparatus constraints in the two experimental conditions, thereby supporting the note of perception-action coupling operating as a control mechanism when performing complex gymnastics skills under changed apparatus constraints. Distributing regulation between and within the cartwheels was different depending on the manipulation of apparatus constraints, and was related to the anticipated effort when achieving the movement goal. **Conclusion:** It can be stated that gymnasts regulate complex motor skills in a foreseeable (i.e., stationary) environment in a way that best suits the current situation in order to accommodate the current configuration of apparatus constraints.

Key words: cartwheel, gymnasts, apparatus, floor, perceived effort, state of motion

REGULACIÓN DEL MOVIMIENTO DE HABILIDADES GIMNASTICAS BAJO VARIAS RESTRICCIONES AMBIENTALES

RESUMEN

Introducción: los gimnastas realizan habilidades complejas en los diferentes aparatos. La estructura percibida de cada aparato en relación con la posición, orientación y estado de movimiento de los gimnastas es un factor importante que influye en la regulación del movimiento. Este estudio se centró en la cuestión de cómo los gimnastas regulan las habilidades complejas en función de las diversas limitaciones de cada aparato. **Método:** gimnastas entrenados realizaron tres volteretas en una fila en dos condiciones experimentales diferentes, con restricciones de aparatos manipulados (aumento y disminución del espacio disponible en el suelo para realizar las volteretas). Se evaluó la estrategia de regulación de los gimnastas en las diferentes condiciones experimentales. **Resultados:** Los resultados revelaron que los gimnastas se adaptaban perfectamente a las restricciones manipuladas del aparato en las dos condiciones experimentales, apoyando así el modelo de percepción-acción, operando como un mecanismo de control cuando se realizan habilidades gimnásticas complejas, bajo las restricciones modificadas del aparato. La distribución de la regulación, entre y dentro de las ruedas del carro, fue diferente dependiendo de la manipulación de las restricciones del aparato, y se relacionó con el esfuerzo anticipado al lograr el objetivo del movimiento. **Conclusión:** Se puede afirmar que los gimnastas regulan las habilidades motoras complejas en un entorno previsible (es decir, estacionario) de la manera que mejor se adapte a la situación actual, con el fin de adaptarse a la configuración actual de las limitaciones del aparato.

Palabras clave: rueda de carro, gimnastas, aparato, suelo, esfuerzo percibido, estado de movimiento

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INTRODUCTION

Gymnasts perform complex motor skills on fixed and stationary apparatuses (Arkaev & Suchilin, 2004; Turoff, 1991). The perceived apparatus structure is one important factor that influences gymnasts' skill performance (Bradshaw & Sparrow, 2001; Davids, Button, & Bennett, 2008; Raab, de Oliveira, & Heinen, 2009). It is thought that gymnasts benefit from a continuous coupling between perception and action in order to regulate their current position, orientation, and state of motion in relation to the environment, and with regard to the current movement goal (Cornus, Laurent, & Laborie, 2009; Fajen, Riley, & Turvey, 2009; Gibson, 1979; Patla, 1997; Warren, 2006). Apparatus constraints, however, may vary naturally in gymnastics as a consequence of gymnasts' current position, orientation and state of motion in relation to the apparatus boundaries. Therefore, the question arises, how gymnasts regulate a complex skill as a function of varying apparatus constraints?

When performing complex skills, gymnasts use current perceptual information to infer the amount of regulation required in a given situation with regard to their current position, orientation, and state of motion, in order to achieve a particular movement goal (Bardy & Laurent, 1998; Bardy & Warren, 1997; Mester, 2000; Patla, 1997). One could easily think of a gymnast running towards the vault apparatus at a high velocity with the aim of performing a Yurchenko vault (Bradshaw, 2004; Penitente, 2014). Arriving at the springboard with a high velocity and placing the feet on the optimal area on the springboard demands an adequate regulation of the approach run (Bradshaw, 2004; Meeuwssen & Magill, 1987; Panteli, Smirniotou, & Theodorou, 2016). Thus, a gymnast performing for instance a Yurchenko vault might use perceptual information about his/her current state of motion (i.e., current position in relation to the vault apparatus together with current running velocity) to regulate his/her run-up steps in a way that allows him/her to perform a round-off in front of the springboard with the aim of an adequate placement of the feet on the springboard (Čuk & Karácsony, 2004; Heinen, Jeraj, Thoeren, & Vinken, 2011). An optimal placement of the feet on the springboard may lead to an optimal recoil during the reactive leap on the springboard, which in turn may lead to an optimal first flight phase that is an important prerequisite for an optimal support phase and so on (Prassas, Kwon, & Sands, 2006).

In such complex motor tasks, the major part of regulation, however, is usually found to occur during the last part of a motor task towards a particular goal or a particular target (Berg, Wade, & Greer, 1994; Lee, Lishman, & Thomson, 1982). Bradshaw (2004) had for instance female expert gymnasts perform Yurchenko vaults. The vaults were videotaped, and several kinematic parameters related to the different phases of the vaults, overall performance in

terms of judges' performance ratings, as well as onset of visual control were analysed (Berg et al., 1994; Bradshaw & Sparrow, 2001). Results revealed that visual control onset occurred in average during the final part of the approach-run. Results furthermore revealed strong correlations between onset of visual control and several key kinematic parameters of the movement phases of the Yurchenko vaults, such as take-off velocity from the springboard and distance of the second flight phase, as well as judges' scores. One may therefore conclude that utilizing visual information about the environment in relation to one's own movement state already early in the approach-run may facilitate later movement phases of the intended vault.

When a gymnast moves, he/she may utilize the visual system to pick up distal information from the surrounding environment such as the shape and position of the various gymnastics apparatuses (Latash, 2008; Vickers, 2007). Picking up distal information may be an important prerequisite for anticipatory movement control because it enables the gymnast to infer 'future' requirements of his/her ongoing movement with regard to the environment, and with regard to the movement goal (Mester, 2000). The current state of motion might only be regulated by exerting forces on the environment when being in contact with any stationary or quasi-stationary object (Bradshaw & Sparrow, 2001; Larsen, Jackson, & Schmitt, 2016). When being airborne, however, gymnasts may anticipate the amount of necessary regulation during the subsequent environmental contact in a given movement situation (Mester, 2000; Patla, 1997, 2003; Turvey, 1992). To do so, gymnasts are on the one hand able to change their body posture in order to regulate rotation during the flight phase, and to regulate (initial) body orientation and body posture for the next environmental contact (Yeadon, 2000). On the other hand, gymnasts are able to pre-program muscular activity that comes into action prior to, and during the upcoming environmental contact(s) (Komi, 2003; Latash, 2008).

In experts, complex motor skills are usually organized to achieve task goals while optimizing energy expenditure at the same time (Cornus et al., 2009; Gautier, Marin, Leroy, & Thouvarcq, 2009). Thus, one important characteristic of a particular movement strategy in a given situation under a particular configuration of constraints is the anticipated level of effort involved in the particular movement strategy (Rosenbaum & Gregory, 2002). Depending on the anticipated level of effort in a given situation, a gymnast might potentially exhibit different regulation strategies in the same skill if there is a strong change in constraints from trial to trial, which in turn requires differing forces to achieve the intended movement goal (Sevrez, Berton, Rao, & Bootsma, 2009; Slobounov & Newell, 1996). For instance, a gymnast might in general perceive a larger effort when performing a cartwheel on the floor with a larger travelled distance than when performing a cartwheel with a smaller travelled distance.

In addition, the implemented amount of required regulation during a particular environmental contact may depend on the dynamics and demands of the current movement (Davids, Button, Araújo, Renshaw, & Hristovski, 2006; Davids et al., 2008). If one is for instance performing a sprint run, the ground contact is significantly shorter compared to walking, and thus directly constrains the options to regulate the current state of motion in a given situation and/or under changed environmental constraints (Bradshaw, Maulder, & Keogh, 2007; Mann & Hagy, 1980).

Apparatus constraints often vary naturally in gymnastics as a result of gymnasts' current position, orientation, and state of motion in relation to the apparatus boundaries. For instance, the area of a gymnastics floor is a square of 12 by 12 meters (FIG, 2017). When a gymnast performs in the diagonal, he/she may use a maximum distance of 16.97 meters from one corner of the floor to the other corner to perform his/her intended sequence of skills. Gymnasts usually try to make the most out of the space available, while at the same time trying to avoid stepping over the border markings of the floor because this results in a deduction (FIG, 2017). Gymnasts are engaged in a variety of situations where they have to regulate their current movement state in a particular sequence of skills with regard to the space available on the floor. It is likely that this regulation will differ from trial to trial due to natural variation of skill execution and thus due to different positions of the gymnast on the floor at the beginning of the skill sequence (Cornus et al., 2009). Thus, already slightly different situations may comprise slightly different gymnast-environment configurations, and consequently might require different regulation strategies in order to accommodate these constraints, and to successfully perform an intended skill or an intended sequence of skills (Bootsma & van Wieringen, 1990; Bradshaw & Sparrow, 2001; Patla, 2003; Svinin, Ohta, Luo, & Hosoe, 2003).

Taken together, it would be logical to assume that if gymnasts have to perform a well-learned sequence of gymnastics skills (i.e., several cartwheels in a row) under changed environmental constraints, such as a reduced space available on the floor to 'fit in' the element sequence, they would have to make spatiotemporal adjustments in the sequence. While spatiotemporal adjustments, however, could be distributed in a manifold of different ways over the course of an action, one could speculate about three different strategies that might be utilized at first instance, compared to when performing without any constraint (Bardy & Laurent, 1998; Montagne, Cornus, Glize, Quaine, & Laurent, 2000; Yilmaz & Warren, 1995): (1) If gymnasts use a *continuous regulation* strategy, the amount of regulation should be constant between each skill (i.e., cartwheel) until gymnasts accommodate their movements to the changed environmental constraint at the end of the skill sequence. (2) If gymnasts use

an *early regulation strategy*, the amount of regulation should be larger at the beginning of the skill sequence, while being small or null towards the end of the skill sequence. (3) If gymnasts adopt a *delayed regulation strategy*, the amount of regulation should be small or null at the beginning of the skill sequence, while increasing towards the end of the skill sequence.

Consequently, if spatiotemporal adjustments are made in one cartwheel, there are different strategies how these adjustments are distributed over the different ground contacts and movement phases of the cartwheel. It may be plausible that most of the regulation occurs during the stance on both feet because it may be easier for a gymnast to simply change the distance of both feet on the ground instead of changing for instance the distance of both hands during the over-head phase of the task. This might also go along with a better perception because visual information is more abundant during the stance on both feet due to the upright position of the body (Asseman & Gahéry, 2005; Bringoux, Marin, Nougier, Barraud, & Raphel, 2000). Nevertheless, regulation may not be limited to the stance phase because if the distance between both feet is too large, a gymnast will hardly be able to perform a cartwheel. Thus, it can be speculated that gymnasts distribute their adjustments between the different ground contacts in a cartwheel. This, however, may again depend on the changed environmental constraints as well as on the perceived level of effort.

It was hypothesized, first, that trained gymnasts would accommodate an experimental manipulation of apparatus constraints (i.e., increased or decreased space available to 'fit-in' three cartwheels in a row) by regulating travelled distance based on perceptual information about the current state of motion in relation to the apparatus constraints in order to achieve the movement goal. Second, it was speculated that gymnasts exhibit different regulation strategies, depending on the perceived level of effort in order to achieve the movement goal under a different manipulation of apparatus constraints. Third, it was expected that regulation is in general pronounced during the stance on both feet while there is less regulation when being in the overhead phase of the cartwheels.

MATERIALS AND METHOD

Participants

Sixteen female gymnasts were recruited to participate in this study (*age* = 16 ± 6 years; [mean \pm standard deviation]). The gymnasts reported an average weekly training extent of 5 ± 3 hours, and they reported to be engaged in artistic gymnastics training since 8 ± 5 years. Gymnasts' task was to perform three cartwheels in a row (see Instruments; Figure 1) in a baseline condition, and in two experimental conditions. The gymnasts were able to perform the

motor task of this study with a high degree of consistency and quality in training and competition (Chi, 2006; Davids et al., 2008). Gymnasts provided informed consent at the beginning of the study, and the study was conducted by taking into account the Declaration of Helsinki and the International Principles governing research on humans, as well as the ethical guidelines of the local ethics committee.

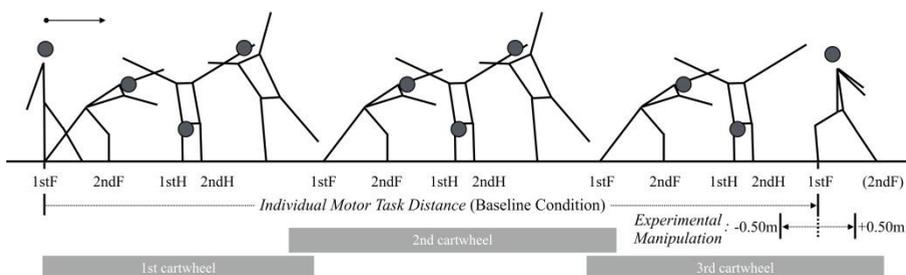


FIGURE 1. Illustration of the motor task (three cartwheels in a row) together with the ground contacts during the cartwheels, and the experimental manipulation. *Notes:* 1stF = ground contact of the *first foot* of the corresponding cartwheel. 2ndH = ground contact of the *second hand* of the corresponding cartwheel. The individual motor task distance (baseline condition) was measured from the ground contact of the first foot in the first cartwheel to the ground contact of the first foot of the third cartwheel.

Instruments

Motor task

The motor task was to perform three cartwheels in a row on a spring floor (Turoff, 1991). The gymnast began the first cartwheel from an upright standing posture with both feet placed together. After swinging one leg up and front, the gymnast brought this leg back to the floor. The leg was slightly bent, and the body started rotating while the hands were brought to the floor in order to invert the body. The straddled legs travelled over the body towards the floor, and the gymnast reached an upright standing posture from which the subsequent cartwheel was performed. The three cartwheels were performed in direct sequence without any additional movement (Figure 1).

Concerning the different ground contacts when performing cartwheels in a row, four different *movement phases* can be distinguished during which a gymnast may regulate the travelled distance of a cartwheel: (1) moving from the first foot support to the second foot support (F → F), (2) moving from the second foot support to the support of the first hand (F → H), (3) moving from the support of the first hand to the support of the second hand (H → H), and (4) moving from the support of the second hand to the support of the first foot (H → F). The next cartwheel then begins with the contact of the first foot after

the overhead phase of the previous cartwheel. The gymnast was asked to come to a stabilized posture at the end of the third cartwheel while facing the opposite direction of motion.

Manipulation of apparatus constraints

Initially, gymnasts were asked to perform six trials of three cartwheels in a row in a baseline condition (BL; see Procedure). The averaged distance between the toes of the first foot in the standing posture and the toes of the first foot contacting the ground in the third cartwheel was defined as *individual motor task distance*. Manipulation of apparatus constraints was realised by either shortening or extending individual motor task distance by 50 centimetres, leading to two experimental conditions (-0.50m condition and +0.50m condition). Gymnasts' task in the -0.50m and +0.50m condition was to perform three cartwheels in a row but this time either shortening (-0.50m condition) or extending (+0.50m condition) the travelled distance in the three cartwheels by 50 centimetres. White adhesive tape (5 centimetres width) was put on the spring floor in order to visually highlight the shortened and extended distance in the two experimental conditions.

Motion analysis system

Gymnasts' performances on the three cartwheels in a row were videotaped by using a full-HD video camera with a spatial resolution of 1920 x 1080 pixels (temporal resolution: 50 Hz). The video camera was placed approximately 25 meters away from the movement plane of the gymnast in order to compensate for potential lens distortion. The camera was also placed orthogonal to the movement plane of the gymnast. The horizontal positions of the toes of each foot during each ground contact of each cartwheel, as well as the positions of the wrists of each hand during each ground contact of each cartwheel were manually digitized in the videotaped sequences by using the software *utilius® easyinspect* (CCC-Software, 2008). The movement area in the which the cartwheels were performed was calibrated by means of a 10 x 3-meter calibration frame, so that the digitized coordinates could be mapped to real-world coordinates. Gymnasts performed six trials of three cartwheels in a row in a baseline condition and in two experimental conditions (+0.50m condition and -0.50m condition), leading to a total of 18 trials.

Measures

In a first step, horizontal positions of the toes and the hands during each cartwheel were averaged over all six trials for each gymnast in each study condition. The horizontal distance of placing the first foot in the third cartwheel thereby indicated the *motor task distance* for each trial (Figure 1). In the second

step, differences in horizontal hand- and foot-positions were calculated between the two experimental conditions and the baseline condition, characterizing the time course of regulation in the two experimental conditions. Additionally, differences between all pairs of adjacent ground contacts were calculated to assess the amount of regulation in each combination of the different hand and feet contacts in relation to the overall motor task distance in the study conditions. In a third step, the aforementioned differences between all pairs of adjacent ground contacts in the two experimental conditions were aggregated for each cartwheel, as well as for each of the different movement phases over all three cartwheels. The values were converted to percentage values, thereby reflecting the relative amount of regulation in each experimental condition with regard to each cartwheel, and each movement phase.

Procedure

The study consisted of three parts. First, after arriving at the gym, the gymnast was informed about the procedure of the study. She was given a 15-minute warm-up phase, as well as three familiarization trials of performing three cartwheels in a row. In the second part, the gymnast was asked to perform the motor task six times in each of the three study conditions, beginning with the baseline condition. The averaged position of the toes of the front foot in the standing posture at the end of the third cartwheel was analysed immediately after the gymnast completed the baseline trials in order to set up the experimental conditions (see Instruments). The remaining twelve trials of the two experimental conditions were presented right afterwards in a randomized order. An instructed experimenter put a white adhesive tape on the spring floor in order to visually highlight the shortened and extended distance in the -0.50m condition and +0.50m condition for each individual gymnast and thus in relation to each individual motor task distance. There was no time pressure in this study and the gymnast was instructed to perform the task as precise as possible. She was allowed to take breaks as desired. In the third part of this study, and after completing the 18 trials of three cartwheels in a row, the gymnast was debriefed.

Data Analysis

Level of significance was defined a-priori ($\alpha = 5\%$). First, and in order to evaluate if gymnasts adapt their motor behaviour to the experimental manipulation in both experimental conditions, two separate one-sample *t*-tests were calculated, comparing the differences of the average motor task distances between the two experimental conditions and the baseline condition to a value

of 0.50 meters (for the +0.50m condition), and to a value of -0.50 meters (for the -0.50m condition).

Second, and in order to assess the nature of gymnasts' regulation strategies, the time courses of regulation in the two experimental conditions (i.e., differences in horizontal hand and foot positions between the two experimental conditions and the baseline condition) were subjected to a regression analysis. In addition, and in order to assess the changes (i.e., increase/decrease) of motor task distance in the different combinations of adjacent ground contacts in the two experimental conditions, separate paired samples *t*-tests were calculated between the two experimental conditions and the baseline condition, taking the differences between all pairs of adjacent ground contacts as dependent variable.

Third, and in order to assess the distribution of regulation over the three cartwheels in the experimental conditions, a 2 (*Experimental Condition*: +0.50m vs. -0.50m) \times 3 (*Cartwheel*: 1st vs. 2nd vs. 3rd) analysis of variance with repeated measures was conducted, taking the relative amount of regulation as dependent variable.

Fourth, and in order to assess the distribution of regulation over the different movement phases in the experimental conditions, a 2 (*Experimental Condition*: +0.50m vs. -0.50m) \times 4 (*Movement Phase*: F \rightarrow F, F \rightarrow H, H \rightarrow H, H \rightarrow F) was conducted, taking the relative amount of regulation as dependent variable. Fisher's LSD post-hoc test was calculated to explore the structure of the significant effects. Cohen's *f* was calculated as an effect size for all significant *F*-values.

RESULTS

Gymnasts' averaged individual motor task distance in the baseline condition was 7.46 ± 0.25 meters (mean \pm SE). Averaged distances between adjacent ground contacts in the baseline conditions were measured as follows (mean \pm SE): F \rightarrow F: 0.74 ± 0.03 m, F \rightarrow H: 0.77 ± 0.03 m, H \rightarrow H: 0.39 ± 0.02 m, H \rightarrow F: 0.58 ± 0.03 m. Gymnasts exhibited a shorter average motor task distance in the -0.50m condition (6.98 ± 0.25 meters), and a longer average motor task distance in the +0.50m condition (7.95 ± 0.25 meters). First, two separate one-sample *t*-tests revealed neither a significant difference between gymnasts' average motor task distance in the +0.50m condition and a value of 0.50 meters, $t(15) = 0.44$, $p = .66$, nor between gymnast's average motor task distance in the -0.50m condition and a value of -0.50 meters, $t(15) = 1.00$, $p = .33$. Gymnasts placed the first foot of the third cartwheel in average -0.48 ± 0.08 meters shorter in the -0.50m condition compared to the baseline condition, and $+0.49 \pm 0.09$ meters longer in the +0.50m condition compared to the baseline condition.

Second, regression analysis of the time course of the differences in hand and foot placement in the experimental conditions compared to the baseline condition revealed that gymnasts' regulation strategies could be fitted satisfactorily by 2nd-order polynomials (each $R^2 > .98$; Figure 2). For the +0.50m condition, the corresponding polynomial equation was: $y_{+0.50} = -0.0032x^2 + 0.0872x - 0.0869$. For the -0.50m meter condition, the corresponding polynomial equation was: $y_{-0.50} = -0.0051x^2 + 0.0349x - 0.053$. Linear regression did not yield satisfactory values for explained variance, and 3rd or 4th-order polynomials did not significantly increase explained variance. Nevertheless, as can be seen from the equations of the polynomials, the weight of the linear part was larger for the +0.50m condition as compared to the -0.50m condition, while at the same time the weight of the squared part was smaller for the +0.50m condition as compared to the -0.50m condition. Additional paired-sample *t*-tests revealed a significant increase of motor task distance in the +0.50m condition for all but the last three pairs of adjacent ground contacts, while at the same time revealing significant decreases of motor task distance for the last six pairs of adjacent ground contacts in the -0.50m condition.

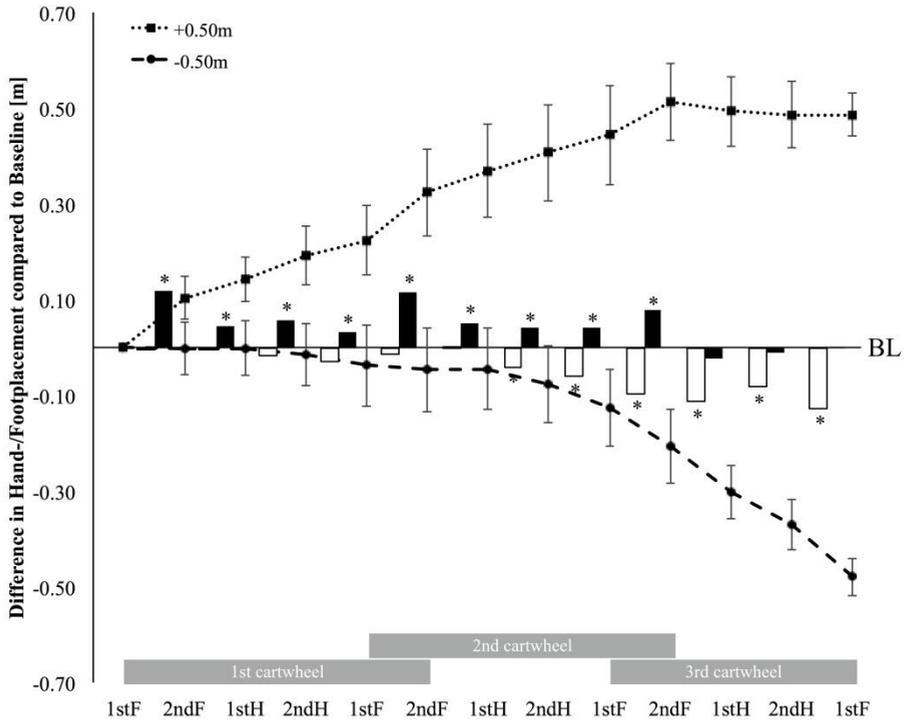


FIGURE 2. Hand placement and foot placement in the three cartwheels. Lines and error bars represent differences between hand and foot placement in the experimental conditions compared to the baseline condition (means \pm 95% confidence intervals). Black columns (+0.50m condition) and white columns (-0.50m condition) represent the amount of regulation (increase/decrease in travelled distance) between two adjacent hand placements and/or foot placements in the experimental conditions compared to baseline condition. * denotes significant difference between experimental condition and baseline condition. *Note:* BL = baseline, 1stF = first foot, 2ndF = second foot, 1stH = first hand, 2ndH = second hand.

Third, analysis of variance revealed a significant interaction effect of *Experimental Condition* (-0.50m vs. +0.50m) \times *Cartwheel* (1st vs. 2nd vs. 3rd) on relative amount of regulation, $F(2, 30) = 13.98, p < .01, \text{Cohens' } f = 0.97$. However, neither the main effect of *Experimental Condition*, nor the main effect of *Cartwheel* reached statistical significance. Post-hoc analysis revealed higher values for relative amount of regulation for the 1st cartwheel, and smaller values for relative amount of regulation for the 3rd cartwheel in the +0.50m condition compared to the -0.50m condition (Figure 3a).

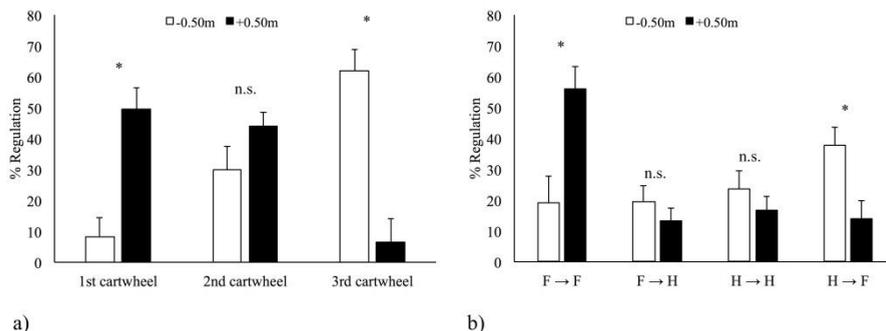


FIGURE 3. Relative amount of regulation (means \pm standard errors) in the three cartwheels (a), and in the different movement phases between contact of feet and hands of the cartwheels (b) as a function of experimental condition. * denotes significant difference between experimental conditions. *Notes:* The amount of regulation was normalized to the amount of overall regulation in the sequence of the three cartwheels. F = foot contact, H = hand contact.

Fourth, analysis of variance revealed a significant interaction effect of *Experimental Condition* (-0.50m vs. +0.50m) \times *Movement Phase* (F \rightarrow F vs. F \rightarrow H vs. H \rightarrow H vs. H \rightarrow F) on relative amount of regulation, $F(3, 45) = 5.61, p < .01$, Cohens' $f = 0.61$. In addition, the main effect of *Movement Phase* reached statistical significance, $F(3, 45) = 5.84, p < .01$, Cohens' $f = 0.62$. Post-hoc analysis revealed that in average, as well as for the +0.50m condition the phase F \rightarrow F exhibited in average higher values for relative amount of regulation compared to all other movement phases. Furthermore, relative amount of regulation was larger in the F \rightarrow F phase for the +0.50m condition compared to the -0.50m condition, while relative amount of regulation was smaller in the H \rightarrow F phase for the +0.50m condition compared to the -0.50m condition.

DISCUSSION AND CONCLUSIONS

This study targeted the question, how gymnasts regulate complex skills as a function of varying apparatus constraints. Trained gymnasts performed three cartwheels in a row under manipulated apparatus constraints, and their regulation strategy in terms of placing the feet and the hands on the floor in different experimental conditions was assessed.

First of all, results revealed that gymnasts almost perfectly accommodated the experimental manipulation in both experimental conditions. This supports the notion that gymnasts use perceptual information to infer the amount of regulation required when performing the cartwheel with regard to their initial and current state of motion in order to achieve the current movement goal (i.e., performing three cartwheels in a row with either decreased or increased motor task distance). Perception-action coupling thus seems to operate when

performing three cartwheels in a row under manipulated apparatus constraints (Cornus et al., 2009; Warren, 2006).

Results furthermore indicated that gymnasts exhibited different regulation strategies in both experimental conditions. Gymnasts did not exclusively use a continuous regulation strategy. In the +0.50m condition, gymnasts regulated the cartwheels continuously during the first two cartwheels, but they only scarcely regulated the third cartwheel because they already accommodated the experimental manipulation towards the ground contact of the second foot in the second cartwheel. In the -0.50m condition, gymnasts only scarcely regulated the first cartwheel, but they started regulation during the second cartwheel, thereby accommodating the experimental manipulation towards the ground contact of the first foot of the third cartwheel. This finding was supported by contrasting the relative amount of regulation in the three cartwheels between experimental conditions. While relative amount of regulation was pronounced in the first cartwheel in the +0.50m condition, it was pronounced in the third cartwheel in the -0.50m condition. One might thus conclude that gymnasts adopted more an early regulation strategy in the +0.50m condition, and more a delayed regulation strategy in the -0.50m condition with a supporting amount of continuous regulation.

Different regulation strategies, however, might result from the perceived effort to achieve the current movement goal (Rosenbaum & Gregory, 2002). On the one hand, gymnasts might in general perceive a larger effort to achieve the movement goal in the +0.50m condition because they have to increase the travelled distance in the three cartwheels compared to the distance to which they are habituated in training. On the other hand, gymnasts could, however, perceive a smaller effort to achieve the movement goal in the -0.50m condition because the motor task distance was smaller than the individual motor task distance in the baseline condition to which gymnasts are habituated. Increasing the travelled distance in a cartwheel can only be achieved by increasing the distances of adjacent ground contacts, and performing the cartwheel with increased distances of adjacent ground contacts is in general more difficult and requires a larger effort than performing the cartwheel with decreased distances of adjacent ground contacts (Slobounov, Hallett, & Newell, 2004).

Gymnasts might encounter natural limits in increasing and decreasing distances of adjacent ground contacts when performing the cartwheel, because at some distances (i.e., extremely wide hand placement or extremely close hand placement) it would be almost impossible to perform a cartwheel anymore in a rule-adequate way (George, 2010). Thus, one could speculate that gymnasts perceive a larger effort to achieve the movement goal in the +0.50m condition and therefore strive to adopt an early regulation of the cartwheels in order to have sufficient regulation capacity towards the end of the skill sequence.

Gymnasts might perceive a smaller effort to achieve the movement goal in the -0.50m condition and therefore utilize a delayed regulation strategy because it could simply be sufficient to initiate regulation when gymnasts perceive a certain necessity to do so during the course of action. This necessity might occur later in the cartwheel sequence because gymnasts' regulation capacity in shortening the motor task distance is sufficient with regard to the experimental manipulation of 50 centimetres.

Results suggest that the early regulation strategy in the +0.50m condition predominantly translates into increasing the distance of the placement of the feet in the stance phase of the (first) cartwheel, while the delayed regulation strategy in the -0.50m condition slightly emphasized decreased distances between placement of the second hand and the first foot of the cartwheels. The stance on both feet provides the most stable contact phase and the largest regulation capacity when performing a cartwheel and thus seems to be most suitable for an early regulation strategy. However, emphasizing regulation between the last hand contact of a cartwheel and the subsequent foot contact seems to be most suitable for a delayed regulation strategy, in particular if the aim is to place the foot on a particular spot at the end of the cartwheel.

Visual information seems to be the most likely information that gymnasts utilize because the visual systems allows to pick up distal information from the environment (Vickers, 2007). Compared to other gymnastics elements, a cartwheel is performed with a rather slow velocity. This might give gymnasts several opportunities to direct their gaze towards the adhesive tape indicating the boundary line on the floor: First, in order to pick up information about the remaining space in relation to the current position, as well as the amount of already performed cartwheels, and second, in order to use this information to anticipate the amount of required regulation in the remaining ground contacts of the subsequent cartwheel(s) (Lee, Young, & Rewt, 1992; Turvey, 1992). Nevertheless, while it seems most plausible that gymnasts direct their gaze towards the adhesive tape during stance on both feet between two cartwheels, it could also be possible that gymnasts look towards the tape during other movement phases of the cartwheel (i.e., overhead position). While this information cannot be inferred from the results of this study, it would be interesting to assess gymnasts' gaze behaviour when regulating complex skills under changing apparatus constraints in subsequent studies.

There are several limitations of this study, and two particular aspects should be highlighted. First, trained gymnasts were recruited to participate in this study. They were able to perform the motor task with a high degree of consistency in training and competition. However, acknowledging that movement regulation strategies differ depending on the current configuration of constraints, it would nevertheless be of interest to assess the (interacting)

role of other constraints (i.e., organismic) on movement regulation in complex skills in gymnastics. One could for instance assume that gymnasts on different expertise levels exhibit different regulation strategies. Assessing regulation strategies in gymnasts of different expertise levels could help clarifying potential invariant characteristics in regulation of complex gymnastics skills as well as those characteristics that change through learning and/or development (Davids et al., 2008).

Second, apparatus constraints were manipulated by either increasing or decreasing the space available to perform three cartwheels in a row. One particular aspect that should be addressed in future studies is gymnasts' capacity to accommodate for changes in apparatus constraints. One could for instance speculate that gymnasts are able to accommodate small or medium changes in environmental constraints. For instance, the gymnasts in this study were able to completely accommodate the experimental manipulation of 50 centimetres. However, a complete accommodation may not occur for rather large or drastic changes, and the question arises to which degree gymnasts may accommodate changes in apparatus constraints of larger size. This may in particular be of interest with regard to apparatuses, such as the balance beam, where imperfect movement regulation may have severe consequences (i.e., not hitting the beam during a landing or reactive leap).

There are, however, some practical consequences and implications that should be taken into consideration. Gymnasts utilized different regulation strategies in different experimental conditions representing different environmental constraints. Nevertheless, it is still common training practice in gymnastics to perform elements in standardized situations in a rather stereotyped manner, thereby often ignoring the important role of regulation processes (Bradshaw, 2004). More innovative training approaches however, should consider that gymnasts' individual movement regulation strategies develop under the influence of the existing configuration of constraints (Davids et al., 2008; Farrow & Robertson, 2017). Instead of acknowledging the development of different regulation strategies in gymnasts as some sort of a by-product of traditional training approaches, it is argued that regulation strategies should rather be put in the focus of gymnastics training (Davids et al., 2006). Introducing a particular amount of practice variability in performing gymnastics elements (i.e., performing cartwheels with different travelled distances from trial to trial) is only one potential idea (Boyce, Coker, & Bunker, 2006; Schöllhorn, Hegen, & Davids, 2012). Such approaches could help enabling gymnasts to perform complex skills under varying (environmental) conditions with a high degree of consistency in training and competition.

It is stated that gymnasts regulate complex motor skills in a foreseeable (i.e. stationary) environment in a way that best suits the current situation in order to accommodate the current configuration of apparatus constraints.

Conflicts of interest

The authors has no conflicts of interest to declare.

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