TOWARD AN IDEAL PERFORMANCE OF CIRCLES ON POMMEL HORSE —CENTRIFUGAL FORCE AND MASS-CENTRE VELOCITY—

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To advance mechanical understanding of circles on pommel horse, we analysed the centrifugal force and the kinematics of whole-body mass centre during circles performed by five high-scored and five low-scored gymnasts. Three-dimensional kinematic and kinetic data were recorded using a motion capture system and force plates set under a no-leg pommel horse. The results showed that the high-scored gymnasts kept a greater mass-centre velocity and centrifugal force during the single-hand support phases than the low-scored gymnasts. It also seemed to be a reasonable interpretation, however, that the double-hand support phases were more complicated and difficult from a mechanical standpoint. Even the high-scored gymnasts who participated in this study might have room for further improvement especially in the double-hand support phases.

KEY WORDS: kinematics, kinetics, rotation.

INTRODUCTION: Among the six events in men's artistic gymnastics, pommel horse is a unique event that is mainly composed of rotational motions on a horizontal plane. Mastering a skill called "circles" is paramount to high level performance since the majority of skills on pommel horse are based on this skill (Figure 1).

---------- Front support phase ---------- Entry phase ------------ Rear support phase -------- Exit phase ----------

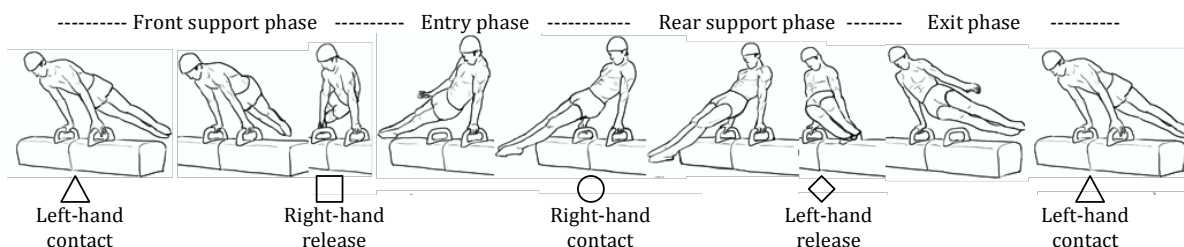| Left-hand contact | Right-hand release | Right-hand contact | Left-hand release | Left-hand contact |

Figure 1: Circles on a pommel horse and the definition of phases. The symbols showing the hand contact and release positions correspond to the symbols in Figure 3.

Fujihara, Fuchimoto, and Gervais (2009) revealed that the rotation of the whole-body mass centre during circles is not circular but rather elliptical on the horizontal plane. It was also reported that the whole-body mass centre moved mainly during the single-hand support phases, and that during the double-hand support phases it slowed down. To explain this phenomenon, Fujihara (2010) introduced a model in which the rotation of the whole-body mass centre is made-up of two conical pendulum swings with some supportive data (Figure 2). During the entry and exit phases (Figure 1), the whole-body mass centre rotates about each supporting hand. During the front and rear supporting phases, in contrast, the whole-body mass centre slows down, and the

Figure 2: The horizontal rotation of the whole-body mass centre is regarded as the composition of two conical pendulum swings (Fujihara, 2010).

fulcrum of the rotational swing switches from one side to the other. Although actual performance of circles is more complicated than such a simplified model, it is still logical to consider that the centrifugal force would play an important role to achieve the greater amplitude of horizontal rotation,
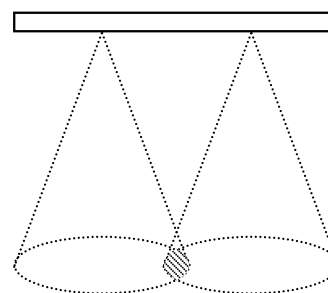
which is one of the key factors to an ideal performance of circles. The purpose of this study was to advance the mechanical understanding of circles by analysing the centrifugal force and the kinematics of the whole-body mass centre and to provide coaches and gymnasts with practical information.

METHODS: We extended the analysis of the data collected for our previous study, so supplement information about the data collection can be found in Fujihara and Gervais (2012).

Participants: Eighteen national-level gymnasts, including four who had international competition experiences, participated in this study. The mass, height and ages of the gymnasts were 47.7 ± 10.8 kg, 1.55 ± 0.11 m, and 16.2 ± 3.6 years. They had 9.4 ± 2.9 years of experience in competitive gymnastics and trained 20.3 ± 3.5 hours per week. University Ethical approval was gained for all experimental protocols, and the gymnast provided written informed consent.

Data collection and analysis: A no-leg pommel horse was cut in half, and each half was fixed to a force plate (AMTI, OR6-6-4000). The force data were sampled with a motion capture system (Qualysis Motion Capture System) via an analogue board. Three-dimensional (3-D) kinematic data were recorded at 100 Hz with 13 Qualisys ProReflex cameras, and the force data were sampled at 1000 Hz. After a warm-up, the participants were fitted with retro-reflective markers on the anatomical landmarks suggested by de Leva (1996) and performed three sets of 10 circles on the pommel horse. For each set of 10 circles, 7 circles (3rd – 9th) were used so that the individual mean data were computed from the data of 21 circles. The 3-D coordinate data were smoothed using a fourth-order Butterworth digital filter at the optimal cut-off frequencies (3.0 Hz – 12.2 Hz). Force data were smoothed at 100 Hz using a fourth-order Butterwortth digital filter and scaled to each gymnast's body weight (BW). The horizontal components of the pommel reaction forces were resolved into a normal direction and a tangential direction, which were determined by differentiating the horizontal trajectory of the mass centre (Fujihara, Fuchimoto, & Gervais, 2009). Then, the centrifugal force was regarded as the force that was of equal magnitude and opposite in direction to the normal component of the pommel reaction forces. Four internationally accredited judges scored the video-recorded circles. A perfect score was set at 10.0 and deductions were applied in step of 0.1 according to technical faults or execution errors. Then, the average of four scores was determined as the final score. The intra-class correlation coefficient, computed as an estimate of the inter-judge reliability, was 0.944. Several circles by three gymnasts showed atypical paths of the whole-body mass centre, data that should be discussed on an individual basis at another opportunity. Therefore, these were excluded from the current analysis. Out of 15 gymnasts, the top five gymnasts were classified into the high-scored group (scores ≥ 9.30), and the bottom five gymnasts were classified into the low-scored group (scores ≤ 8.50). The Wilcoxon-Mann-Whitney *U* test was used to compare the high-scored group to the low-scored group, and the dominance statistic (Cliff's *d*, Cliff, 1993) was computed as an effect size measure. The traditional *α* level 0.05 was selected for each test to compensate the low statistical power due to the small sample although the inflation of the family-wise error rate was expected due to multiple univariate statistical tests.

RESULTS: The horizontal trajectories of the whole-body mass centres were elliptical for both the high-scored and the low-scored groups (Figure 3). Also, the whole-body mass centre had a greater velocity during single-hand support phases than during double-hand support phases.

When compared between the two groups, the magnitude of the normal component of the horizontal reaction forces, namely the magnitude of the centrifugal force was greater for the high-scored group (Table 1). In particular, there were significant differences in the entry and exit phases. Although the mean values of those in the double-hand support phases were also greater for the high-scored group, the greater variability contributed to no significant difference from a statistical perspective.

The horizontal velocity of whole-body mass centre was also greater for the high-scored group (Table 1). As well as the normal component of horizontal reaction forces, statistical significances were found only in the single-hand support phases. In terms of the peak values, the maximal velocities were 0.88±0.06 vs. 0.73±0.05 in the entry phase, and 0.91±0.08 vs. 0.77±0.07 in the exit phase (m/s, high-scored vs. low-scored). Additionally, the minimal velocities were 0.32±0.07 vs. 0.24±0.07 in the front phase and 0.21±0.07 vs. 0.21±0.04 in the rear support phase (m/s, high-scored vs. low-scored). The high-scored gymnasts kept a greater velocity for the whole-body mass centre in all phases but the rear support phases.
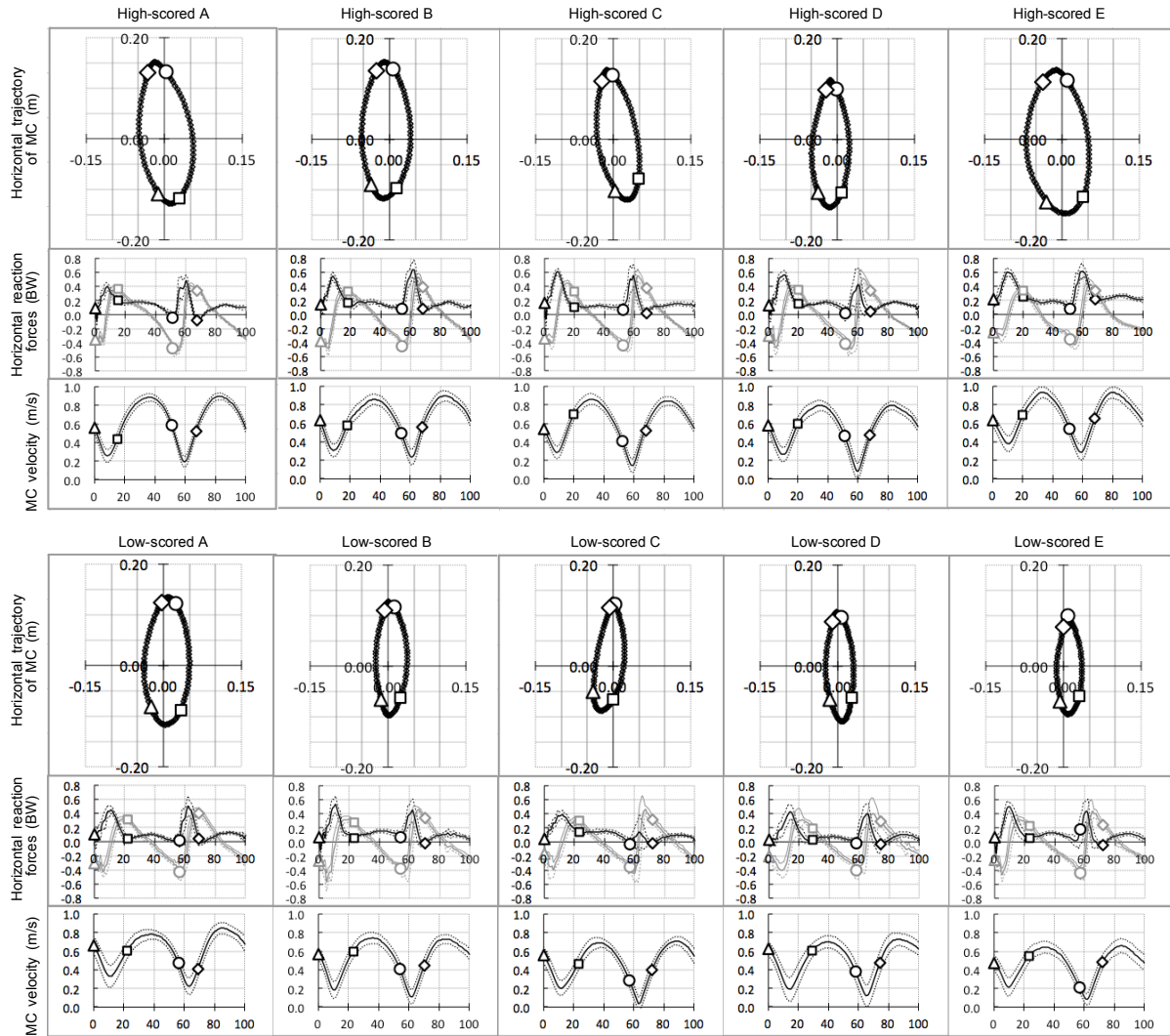
Figure 3: The horizontal trajectories of the whole-body mass centres, the horizontal components (normal –black, tangential-grey) of the pommel reaction forces, and the horizontal velocities of the whole-body mass centres during circles. The upper three rows show the high-scored group of five gymnasts, and the lower three rows show the low-scored group of five gymnasts. All graphs were based on the average of 21 circles, and the broken lines indicate the ±1 standard deviation. The symbols in the graphs correspond to the symbols in Figure 1, depicting the hand contact and release phases.

Table 1: The comparisons of the mean values between the high-scored and low-scored groups.

Variables (Unit)	High-scored (*n*=5)	Low-scored (*n*=5)	Difference	Cliff's *d*	*P*	
Normal component (BW)						
Front phase	0.33±0.06	0.23±0.03	0.10	0.72	0.056	
Entry phase	0.15±0.03	0.09±0.03	0.06	0.84	0.032	*
Rear phase	0.29±0.08	0.17±0.09	0.12	0.68	0.095	
Exit phase	0.14±0.06	0.07±0.01	0.07	0.84	0.032	*
Mass-centre velocity (m/s)						
Front phase	0.45±0.06	0.42±0.05	0.03	0.32	0.421	
Entry phase	0.77±0.04	0.68±0.06	0.09	0.92	0.016	*
Rear phase	0.39±0.06	0.38±0.04	0.01	0.12	0.841	
Exit phase	0.79±0.06	0.67±0.06	0.12	0.84	0.032	*

DISCUSSION: In general, the high-scored gymnasts kept the greater centrifugal force and the greater horizontal velocity of the whole-body mass centre, which should be beneficial in maintaining better technical amplitude in the circles. Significant differences between the high-scored and the low-scored groups were found more in the single-hand support phases than in the double-hand support phases.

One possible interpretation is that skill levels are more discernible in the single-hand support phases. Several previous studies reported that skilled gymnasts showed longer single-hand support phases and shorter double-hand support phases than unskilled gymnasts (e.g. Baudry, Leroy, & Chollet, 2003). A dynamic but well-balanced rotation about the supporting arm during a single-hand support phase seems to be one of the key to an ideal circle.

Another possible interpretation is that keeping the mass-centre velocity and the centrifugal force high during the double-hand support phases are more difficult than during the single-hand support phases. As a result, even the high-scored gymnasts in this study were not skilful enough to show the clear difference from the low-scored gymnasts. The relatively greater variability especially in the rear support phases supports this assertion. According to Baudry et al. (2009), the shoulder joint angle particularly in the rear support phase differentiated the level of circles in terms of its amplitude. Nakamura and Shuto (2002) discussed the difficulty of catching and supporting on the right hand, which has to be done in one's backside. The difficulty of the rear support phase was partially attributed to the limited shoulder flexibility (Fujihara, 2010). All together, there may be room even for the high-scored gymnasts in this study to further improve their circles related to the rear support phase.

What is important to understand is that not only the velocity but also the radius of rotation also plays an important role to have a large centrifugal force. No matter how fast the mass centre moves, a linear motion has nothing to do with centripetal and therefore centrifugal forces. Relatively large within-gymnast and between-gymnast variability during the double-hand support phases and the transitional phases implied its possible difficulty. According to the model presented by Fujihara (2010) (Figure 2), the single-hand support phase seems to be simpler from a mechanical perspective because of its single fulcrum. The double-hand support phase, in contrast, appeared to be more complicated. That is, a gymnast has to switch the supporting arms for a short time period (approximately 0.1-0.2 s) and thus make a dramatic change in the direction of the rotation in order to connect two pieces of circular motions that have different centres of rotations. From these viewpoints, the double-hand support phases could be more problematic than the single-hand phases. In other words, more key factors to an ideal performance of circles may yet be hidden.

CONCLUSION: Based on the data of mass-centre rotation, its velocity, and the centrifugal force, we discussed the rotational mechanics of circles to provide coaches with practical information. The high-scored group demonstrated a greater mass-centre velocity as well as a greater centrifugal force during the single-hand support phases. It would appear that the key to an ideal performance of circles may lie with the double-hand support phases.

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