KINEMATIC AND KINETIC ANALYSIS OF COUNTER MOVEMENT JUMP VERSUS TWO DIFFERENT TYPES OF STANDING BACK SOMERSAULT

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Abstract

The aim of this study was to compare the take-off's kinetic and kinematic variables between three types of jumps from a standing position: counter movement jump with arm swing (CMJa), standing back somersault with landings on the spot (BSls) and standing back somersault with rear displacement at landing (BSld). Five elite level male gymnasts (age 23.17 ± 1.61 years; height 165.0 ± 5.4 cm; weight 56.80 ± 7.66 kg) took part in this investigation. A force plate and a 3D movement analysis system were synchronized and used for data collection. Statistical analysis via non-parametric Kruskal-Wallis test showed a significant difference between the take-off variables. The vertical component of force, peak power, impulse and displacement of the centre of mass were significantly different (P<0.01). Similarly, the horizontal component of force, maximum speed, peak power and displacement of the centre of mass were significantly different (P<0.01). However, vertical velocity remained relatively constant. In conclusion, the standing back somersaults performed on the spot’s variables (without back displacement) were very similar to the ones analysed during counter movement jump with arm swing. The standing back somersault with landing on the spot allowed better force impulse. This was facilitated by a take-off closer to the centre of mass, unlike the standing back somersault with rear displacement in landing. Analysing kinetic and kinematic together, allowed the endorsement of linear regression equations enabling the prediction of some variables from others.

Keywords: gymnastics, take-off, thrown off centre, reaction force.

INTRODUCTION

Jumps take an important part of gymnastics men and women’s daily routines. Gymnasts’ ability to transmit their impulse from their feet to their upper bodies following rebounds is crucial, allowing acrobatic skills such somersaulting and twisting. Artistic gymnastics has seen amazing evolution throughout the last five decades (Jemni, Friemel, Sands & Mikesky, 2001). Exhibited strength, power, flexibility and spatial awareness via the incredible complicated aerial skills have contributed in shaping a new profile of the modern gymnast (Jemni, 2011; Jemni, Sands, Friemel, Cooke & Stone, 2006). This lately is nowadays able to perform triple tacked
somersaults and even quadruple twists in one straight back. How could they do it? How important is to learn the “perfect” jumping technique? Are there any variables to analyse enabling coaches to dissociate the “good”, the “bad” and the “useful” jumps?

Vertical jumps are used in a plenty of sports. Their primary goal is usually to reach the greatest possible height (Psycharakis, 2012). Other goals could also include rotation in acrobatic somersaulting. Gymnasts’ jumping ability is often linked to successful performance (especially in floor routines and vault) and is sometimes considered as an overall indicator of gymnastics proficiency. Gymnastics’ performance is largely defined by the ability to successfully jump complex forward and backward rotating skills. Video analysis of world-class gymnastics competitions has shown gymnasts performing more backward rotation skills than forward ones (McNitt-Gray, 1992; Munkasy, McNitt-Gray, Michele & Welch, 1996; Harski, 2002; Sadowski, Boloban, Wiśniowski, Mastalerz, & Niżnikowski, 2005). This current study would put some more insight on the nature of the backward take-offs. Analysing the mechanics of ground reactions forces during different jumping cases could add significant understanding and tools for coaching. Reaction force passes through the centre of mass (COM) during vertical jump; meanwhile this force would be thrown off centre forward during a backward rotation. Performing somersaults from a standing position requires a production of significant amount of force and velocity during take-off phases. The transfer of force depends on the gymnast’s ability in backward rotating skills. Relatively large number of authors have analysed various executions of backward somersaults (Payne & Barker, 1976; Bruggemann, 1983; Lacouture, Junqua, Duboy, & Durand, 1989; Knoll, 1992; Newton, Turner, & Greenwood, 1992; Hong & Brüggemann, 1993; McNitt-Gray, Munkasy & Welch, 1994; Duboy, Junka, & Lacouture, 1994; Medved, Tonkovic & Cifrek, 1995). Conversely, there is a paucity of literature that explores ground reaction forces during take-offs. McNitt-Gray, Hester, Mathiyakom and Munkasy (2001) studied the mechanical demand during landing after three skills: the forward somersault, the backward somersault and the drop jump. Medved (2001) has studied ground reaction force during gymnasts’ take-off while performing two skills: backward somersault and straddle jump, both performed from a standing position. Lebeuf, Lacouture and Bessonnet (2003) analyzed the COM path during a successful and a failed backward somersault. Other studies have examined the vertical jump as in artistic gymnastics (Marina, Jenni & Rodríguez, 2012; Sands, 2011; Sands, Stone, McNeal, Jenni & Haff, 2006; Swartz, Decoster, Russell & Croce, 2005; Marina, Busquets, Padulles & Camps, 2005; Marina, 2002). Very recently, Marina, Jenni, Jimenez & Rodriguez (2012) have thoroughly investigated jumping abilities in significant number of gymnasts and compared them to a matching control group. They have come-up with a very important conclusion showing that studying jumping ability should take few variables into consideration. Flight time, contact time and power output are not enough to dissociate gymnasts; other variables such as Bosco expression and flight to contact times ratio should also be calculated for a more significant profiling purpose. For these reasons, the current study has not only analysed dynamic data acquired by a force plate but also kinematic data collected by synchronised cameras.

The purpose of this study was to compare the take-off’s kinetic and kinematic variables underpinning gymnasts’ ability to perform the counter movement jump with arms swing (CMJs), the standing back somersault with landing on the spot (BSls) and the standing back somersault with rear displacement in landing (BSld).

METHODS

Five elite level male gymnasts (age 23.17 ± 1.61 yrs; height 165.0 ± 5.4 cm; weight 56.80 ± 7.66 kg) took part in this
study. The inclusion criteria were: to be ranked at international level with participation in world cups and/or championships; average training volume around 25 hours per week; healthy without any muscular, neurological or tendinitis injuries; able to perform back somersaults on the spot. After being informed on the procedures, methods, benefits and possible risks involved in the study, each subject reviewed and signed a consent form to participate in the study. The experimental protocol was performed in accordance with the Declaration of Helsinki for human experimentation and was approved by the university ethical committee.

The investigation’s design contained a dual approach: kinematic and kinetic of three types of take-offs from a standing position. The direction of reaction forces was different between the three skills during the push-off phases (Figure 1):

- It passes through the centre of mass (COM) during the counter movement jump with arm swing (CMJa) (Figure 1a);
- It is thrown off centre forward but close to the COM during the standing back somersault with landings on the spot (BSls) (Figure 1b);
- It is very thrown off centre forward during the standing back somersault with rear displacement at landing (BSld) (Figure 1c).

Figure 1. Kinogrammes of three types of take-off from a standing position. (a) counter movement jump with arm swing; (b) standing back somersault with landings on the spot; (c) standing back somersault with rear displacement in landing.

Kinetic data were acquired using a 60×40 cm Kistler force plate (Kistler Instruments, Switzerland. Ref. 9281C). Sampling frequency was 500 Hz, and the measuring range was set between 10 to 20 kN. Vertical (Fy) and horizontal (Fx) force variables, the COM displacement (dx; dy), velocity (vx; vy), peak power (Px; Py) and impulse (Ix; ly) were analysed. Analysis was performed with a Bioware Performance Software 5.1.1 (Kistler Instruments, Switzerland).

Kinematic data were acquired using two high-speed cameras (NAC HSV-500C3; 250 Hz) in NTSC format with VCR C3D and SVHS tape. A motion analysis software (Movias, NAC Corp, Santa Rosa, CA) was used to process the data. 20 retro-reflective body markers were attached to the gymnasts’ bodies allowing digitisation using a video based data analysis system (Movias for Windows 2.0.4). The body segments’ centres of mass were computed using Matshui model (1983). Take-off angle (αT), shoulder angle (αS), hip angle (αH) and knee joint angle (αK) were analysed and compared at the different take-offs. Angular displacements of these respective joints (θS, θH and θK) and their angular velocities (ωS, ωH and ωK) were calculated in the sagittal plane. Data acquisition and testing were carried out in a laboratory setting. All tests were performed within a 3-day period, starting at 4:00 PM up to 6:00 PM under the following environmental condition: average temperature 23°C (minimum 20, maximum 26°C). The force plate was synchronized with the two high-speed cameras. The first camera was placed in front of the subject and the second sideways, each at 5m from the centre of the force plate (figure 2). All participants wore only a short during testing to allow digitising. They were given ten-minute warm-up period including light jog, stretching and several jumps and somersaults with stable landing. Each gymnast performed each jump three times in separate days. The choice of jumps and/or somersaults was randomised using Latin Square randomisation protocol (Zar, 1984).

The execution of each skill was separated by a two-minute recovery period between repetitions. Two international
judges marked each somersault by referring to the Code of Points FIG (2009). Only the best somersault was retained for analysis and comparison.

Figure 2. Experimental setup.

Data are reported as mean ± standard deviation (SD). The distributions’ normalities, estimated by the Kolmogorov-Smirnov test, varied between variables. Therefore, we used the non-parametric Kruskal-Wallis test to compare all take-offs’ variables, while the U test of Mann-Whitney was applied to pair-wise the somersaults and CMJ comparison. Spearman correlation analysis was performed to check any relations between the CMJ and the back somersaults. The results are considered significantly different when the probability is less than or equal to 0.05 ($P \leq 0.05$). Statistical analyses were performed using the software package SPSS version 13.0 (SPSS Inc., Chicago, IL, USA).

RESULTS

All kinetic data for the BSld have almost doubled in comparison to the tow other conditions. Significant statistical increases were noticed in all horizontal components: the horizontal force component ($F_x$) has increased by 63.36% during the BSld when compare to the CMJa and by 39.18% when compared to the BSls ($P<0.01$) (Table 1). Similar results were noticed for the horizontal velocity ($v_y$): [+41.36% compared to CMJa ($P<0.05$), (+51.49% compared to BSls ($P<0.01$)], the horizontal peak power ($P_x$): [+50.87% compared to CMJa ($P<0.01$) and +50.34% compared to BSls ($P<0.01$)] and the horizontal impulse ($I_x$): [+36.23% compared to CMJa ($P<0.05$) and +51.03% compared to BSls ($P<0.01$)] (Table 1).

The magnitude of change has ranged between 10% to 22% when it came to compare the vertical components. Force vertical component ($F_y$) has significantly increased by 10.04% during the CMJa in comparison to the BSld ($P<0.01$). Similarly, peak power’s vertical component ($P_y$) has significantly increased during the same take off compared to the tow other conditions: [by 19.031% compared to BSld ($P<0.01$) and by 11.81% compared to BSls ($P<0.05$)].

Looking at the absolute data, the CMJa and BSls showed the highest level of vertical force, followed by BSld (1808.89 ± 97.06 N; 1806.87 ± 78.08 N; 1625.55 ± 62.64 N respectively). Moreover the horizontal component of force was the highest during the BSld take-off (very thrown off centre). The BSld developed more force than the BSls and the CMJa (209.44 ± 4.80 N; 126.65 ± 22.14 N; 127.38 ± 7.97 N respectively) (Figure 3).

Figure 3. Horizontal and vertical forces produced during the three take offs.

Vertical axis’ variables were different during the impulse of the three take-offs (214.91 ± 9.37 N/s; 194.72 ± 3.82 N/s; 176.31 ± 20.82 N/s respectively for CMJa, BSls and BSld). Moreover, the horizontal axis of the impulse was higher during the BSld compared to the BSls and to the CMJa (23.80 ± 3.84 N/s; 18.28 ± 2.68
respectively). This increase is indeed a basic condition allowing backward rotation, and is supported by the fact that power generated on the horizontal axis was greater during the BSld compared to BSls and CMJa (279.00 ± 60.34 W; 138.08 ± 35.00 W; 137.54 ± 27.62 W respectively). In contrast, the peak power produced on the vertical axis was more important during CMJa and BSls than during BSld (4774.12 ± 231.98 W; 4269.72 ± 245.65 W; 4010.94 ± 368.00 W respectively) (Figure 5).

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<th>Table 1. Comparative statistics of the three take-offs.</th>
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* Significant at P < 0.05; ** Significant at P < 0.01

Kinematic study has provided the following results: the take-off angle (αT) relative to the vertical axis was significantly decreased in the BSld condition in comparison to the two other conditions (P<0.01): by 5.01% and by 13.45% compared to BSls and to CMJa respectively. Similarly, the angle of shoulder joint at take-off (αS) was also significantly decreased by 18.22% during the BSld compared to the CMJa (P<0.05). The angle of knee joint at take-off (αK) was significantly decreased at almost a similar percentage during the same skill compared to CMJa (18.72%) (P<0.01) (Figure 6).
Furthermore, the angular displacement of the shoulder joint ($\theta_S$) was significantly increased by 9.65% in the CMJa condition compared to BSld ($P<0.01$). More considerable change was noticed in the hip joint. Its angular displacement ($\theta_H$) has significantly increased compared to the two other conditions ($P<0.01$): by 34.50% and by 14.70% compared to BSld and to BSls respectively.

Angular displacement of the arms was larger during the CMJa compared to the BSld (157.51±6.77° and 128.81±7.63° respectively) and the flexion of the hip joint was also more important (55.48±2.05°; 47.32±2.36° and 36.33±2.65° respectively for CMJa, BSls and BSld). Angular velocity of the knee joint ($\omega_K$) was likewise increased during the CMJa compared to the other situations by 27.95% v BSld ($P<0.01$) and by 19.70% v BSls ($P<0.05$). The angular velocity of the shoulder joint ($\omega_S$) was itself, significantly increased in the BSld condition with respect to the two others ($P<0.05$): by as high as 65.53% compared to BSls and by 71.86% compared to CMJa (Figure 7).
vertical peak power (Py) and the angle of the hip joint ($\alpha_H$) ($r = 1.000$).

Figure 8. Correlation between SBls and CMJa

**DISCUSSION**

This study is focused on the variables that could affect the take-off phases by comparing them between three different jumps/skills. It is indeed well documented that different types of take-offs significantly affect the range of motion (ROM) of the lower limbs and therefore the entire height of the jump and the resultant power output (Marina, Jemni & Rodriguez 2012). In this study, the angle of the knee joints ($\theta_z$) was significantly higher during the CMJa than during the BSls and the BSld. This variation of ROM during the take-offs could be explained by the direction of reaction force with respect to the COM. If the direction of the force is off COM this could lead to some “wasted effort” and therefore not enough height could be reached. Several studies confirmed that the optimal knee angle that produced the best vertical displacement in gymnasts was around 90° (Salles, Baltzopoulos and Rittweger 2011, Moran and Wallace 2007, Mathiyakom, McNitt-Gray and Wilcox 2006). In this current study, the five gymnasts have reached an average height of 0.71 ± 0.04m during the CMJa, whereas they only reached 0.65 ± 0.04m and 0.60 ± 0.03m during the BSls and BSld respectively (Figure 9). Their horizontal displacement, however, was expectedly the highest during the BSld, caused by a take-off very thrown off centre and allowing rotation, as described by Medved et al. 1995; Munkasy et al. 1996; Medved 2001; Leboeuf et al. 2003.

Our investigation confirms, as previous studies, that CMJ allows more significant displacement. This was indeed shown by the knees’ angle that was significantly more important during the CMJs’ take-off compared to BSld and to BSls. Clansey and Lees (2010) suggested a strong relationship between the ROM of the knee and the hip joints during the vertical jump. This could explain the large knee amplitude during the CMJa in our study.

Table 2 highlights the main kinetic and kinematic findings of this study in comparison between the three take-offs. Comparison between the back somersaults showed that the BSld developed less force
and impulse on the vertical axis compared to the BSls. However, there was a significant increase of the strength, maximum speed, impulse, peak power and displacement at the horizontal axis, as suggested by Medved (2001) and Leboeuf et al. (2003). Comparison between the BSld and CMJa showed, indeed, a very significant difference for all variables except for the vertical velocity of the COM that remained almost at the same level (Table 1). These results confirm similar investigation by Leboeuf et al. (2003), in which they showed that gymnast would miss the back somersault if he was inclined backwards during the take-off. Contrariwise, there was a great similarity between the CMJa and BSls in most variables, with the exception of the vertical impulse and peak power that were significantly lower, as also suggested by other authors (McKinley and Pedotti, 1992; Medved 2001; Mc Nitt-Gray 2001).

Table 2. Variation of the main kinetic and kinematic variables at three take-offs.

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<th>Variables</th>
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*Where: (↗) is increase; (↘) is decrease.

The increased horizontal force during the BSld was firstly caused by the take-off, which was thrown off centre, secondly by a surplus of horizontal displacement as suggested by (Mc Nitt-Gray, 2001; Medved 2001; Leboeuf et al. 2003). Leboeuf et al. (2003) mentioned that, if a back somersault is performed correctly, the pulse force would be around 200 N/s. These figures are indeed higher than the ones found in the current study as our gymnasts’ force pulse ranged between 194.72 ± 3.82 N/s; 176.31 ± 20.82 N/s respectively for the BSls and BSld (Figure 4). This difference might be related to the fact that our gymnasts performed the somersaults on the spot whereas in Leboeuf et al. (2003)’s study, they performed it after a snap down.

Interestingly, the correlation analysis showed a significant relation between CMJa and BSls at the force’s vertical component and the displacement of COM (R² = 0.94; R² = 0.78 respectively). Moreover, correlation analysis between kinetic and kinematic variables showed significant relations between the following: take-off angle (αT) and horizontal displacement (dx) (R² = 0.89); vertical force component (Fy) and angular displacement of the knees joint (θK) (R² = 0.75); vertical peak power (Py) and the hips joint angle (αH) (R² = 0.97). Thus, we could suggest a linear regression to predict the kinetic performance variables from the results of the kinematic study and vice versa. The regression equations would be:

**Prediction of kinetic variables from kinematic data:**

\[ dx (m) = -2.26 + (-0.02 \times \alpha_T (°)) \]
\[ F_y (N) = 2429.88 + (-9.26 \times \theta_K (°)) \]
\[ P_y (W) = -185737.31 + (1061.23 \times \alpha_H (°)) \]

**Prediction of kinematic variables from kinetic data:**

\[ \alpha_T (°) = 91.48 + (-36.02 \times d_x (m)) \]
\[ \theta_K (°) = 219.35 + (-0.08 \times F_y (N)) \]
\[ \alpha_H (°) = 175.16 + (0.00 \times P_y (W)) \]

*Where: (dx) is the horizontal displacement of the COM; (Fy) is the
vertical force component; \( (Py) \) is the vertical peak power; \( (\alpha_T) \) is the take-off angle; \( (\theta_K) \) is the angular displacement of the knee joint; \( (\alpha_H) \) is the angle of hips joint.

The above equations could indeed be considered as a “god saver” for those who can’t afford kinematic lab facilities. Some kinematic variables could indeed be predicted based on accurate kinetic data collection and vice versa.

**CONCLUSION**

The purpose of this study was to compare the take-off’s kinetic and kinematic variables between (CMJa), (BSls) and a (BSld). Kinematic analysis showed that gymnasts performed a more important flexion of the knees and an inclination of the trunk during the CMJa than during the two other standing back somersaults. This range of motion seems to allow for better vertical force, displacement and peak power. In addition, it allows a minimum loss of force and power on the horizontal axis.

The kinetic analysis showed great similarities between the BSls and the CMJa variables of strength, impulse, displacement and peak power on both the vertical and horizontal axis. As for the BSld, this take-off very thrown off centre forward, seemed to disfavour the gymnast from reaching a maximum elevation of the centre of mass during the standing back tucked somersault.

As expected, the take-off that passes through the COM, allowed better amplitude of movement than the take-offs thrown off centre forward. The CMJa and BSls showed the highest level of vertical displacement, force and peak power followed by BSld. This implies that, for a better performance of the standing back somersault, it is necessary that the impulse pass through the nearest point to the COM. Investigating kinetic and kinematic variables together, allowed the endorsement of linear regression equations enabling the prediction of some data from others. As practical implications, we recommend coaches to carefully monitor the position of gymnast's shoulders and to avoid a backwards inclination at the take-off during a standing back somersault.

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