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**Journal:** *Journal of Applied Biomechanics*

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Kinematic landing strategy transference in backward rotating gymnastic dismounts

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Funding: None

Conflict of Interest Disclosure: None

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Running Title: Landing strategy transference in gymnastic dismounting

Word Count: abstract 166 words; body of text: 3391 words
Abstract

The aim of this study was to develop insight into the transference of kinematic landing strategies between backward rotating dismount skills. Female gymnasts performed backward rotating pike (N = 4 x 10 trials) and tuck dismounts skills (N = 4 x 10 trials) from the beam apparatus. Whole and lower body joint kinematic measures were quantified for the impact phase using an automatic motion analysis system (CODAMotion). Phase duration, whole body orientation and the mass centre maximum z-displacement were similar (p< .01) between skills for individual gymnasts and the group. While skill differences in the hip joint motion profiles were notably larger (group RMSD: 30.9%) than the ankle (group RMSD: 13.6%) and knee (group RMSD: 15.4%) joints, individual gymnast adjustments were made to the discrete joint kinematic measures. The use of a stable whole body orientation may provide important indicators of effective strategy transference between fundamental dismount skills. Further consideration of the joint strategy adjustments made according to the gymnast’s performance level may however be warranted.

Keywords: artistic gymnastics, beam apparatus, impact mechanics
Introduction

The dismount is a critical element of gymnastic routines and comprises an aerial and landing phase, where the onset of each are established by the loss of contact with the apparatus or floor and the subsequent first contact with the landing surface, respectively\(^1\). Performance objectives for the aerial and landing phases are guided by the prescribed kinematic strategy (movement patterns) defined by the Fédération International de Gymnastique Code of Points\(^2\). The gymnast must attempt to adhere to the kinematic strategy criteria e.g. landing without excessive knee flexion and a subsequent deep squat, in order to minimise point deductions. Unlike the aerial phase, which requires a focus on successfully addressing the prescribed performance criterion of a skill, combined performance and injury objectives must be simultaneously addressed in the landing phase. While not explicitly defined within the Fédération International de Gymnastique\(^3\) Code of Points, a safe, aesthetic and well-executed landing must be achieved to complete the dismount\(^1\). The ability of a gymnast to satisfy the multiple requirements of competitive landing tasks have subsequently been linked to performance errors (e.g. due to multiple foot placement and unnecessary segment movements) and high incidence rates of injury\(^3\).

As highlighted previously\(^4\), injury is the most serious problem faced by modern-day gymnasts and largely occurs as a result of acute or chronic impacts. During dismounting, gymnasts are exposed to rapidly occurring and high magnitudes of impact forces. The forces experienced on the lower body and subsequent potential for injury have been closely linked to the kinematic landing strategy employed in landing\(^5,6\). The minimisation of point deductions and maximisation of safety in dismounting has previously been considered achievable by the development and mastery of a pre-programmed kinematic strategy\(^1\). The kinematic landing strategy employed has traditionally been examined using velocity-controlled landing tasks from specified drop heights. Regulatory kinematic changes such as
the use of greater and more rapid knee and hip flexion in controlled drop landing and stop-jump manoeuvres respectively, were suggested as primary indicators of a safe and efficient landing strategy. However, the potential for modified landing strategies in more complex gymnastic tasks or skills has previously been recognised. Strategies used in drop landings were further suggested to not be completely applicable to gymnastic landings, which involve more rapid angular velocities prior to impact. While insight into the mechanics of more complex gymnastic-style landings has been achieved, limited understanding of the regulation of loading in more challenging dismounts typically exists.

When compared to velocity-controlled landings, the landing phase of gymnastic elements requires the same mechanical objectives to be met at a total body level e.g. the execution of a safe and aesthetic landing. However, the need to achieve more rapid angular velocities and prescribed movement patterns associated with distinct skills e.g. pike and tuck somersaults in the aerial phase of gymnastic dismounts potentially demands a skill-specific pre-programmed landing strategy. Changes in kinematic landing strategies according to modulated task constraints such as the impacting surface and vertical drop height have previously been reported. Differences in lower extremity orientations relative to the ground reaction forces have for example, been established in landing strategies executed following a front and back salto (somersault). The use of a modified landing strategy between salto skills was suggested to provide functional benefits in allowing gymnasts to land under diverse initial momentum conditions. In dismounts performed with differing vision constraints, the use of a common kinematic strategy between conditions had contrastingy been suggested. According to the theory proposed by Bardy and Laurent, the use of a consistent strategy between conditions may be indicative of gymnast expertise. However, contradictions in the extent to which kinematic landing strategies are modified between tasks or skills may be partially explained by individual gymnast responses. McNitt-Gray et al. highlighted
gymnast-specific kinematic adjustments to changes in drop height and mat surface, which may suggest the execution of self-selected rather than task-defined landing strategies. Simultaneous within gymnast and group analyses may therefore be warranted to provide insight into mechanisms of skill transference of kinematic landing strategies in gymnastic dismounts.

Establishing pathways for effective skill development has recently been highlighted as a key component of the coaching process in gymnastics\textsuperscript{14}. A gymnast-specific variability in the multi-joint kinematic strategy used in backward rotating dismounts has been reported and considered to allow self-specific modifications in joint loading and subsequent injury potential in dismounting\textsuperscript{10}. Insight into idiosyncratic and skill-specific kinematic indicators of safe and efficient landing strategies may accordingly assist gymnastic skill development in dismounting by facilitating the implementation of customised individual or skill-based training programmes.

Backward rotating pike and tuck somersault dismounts from beam may be considered fundamental dismount skills for competitive gymnasts to master\textsuperscript{10}. The pike and tuck skills, which are illustrated in Figure 1, are characterised by diverse whole body moment of inertia requirements in the latter stage of the aerial phase. When compared to the tuck skill, a relatively larger moment of inertia about the transverse axis is achieved in the respective stage of the pike skill. A skill-specific landing strategy to accommodate the preceding aerial phase may subsequently be demanded. The aim of this study was to gain insight into the idiosyncratic and common whole body and joint kinematic landing strategies selected for the execution of backward rotating somersault dismounts (pike and tuck) from the beam apparatus. The overall purpose of this study was to investigate the potential for kinematic landing strategy transference between fundamental dismount skills to assist the establishment of effective skill development pathways in gymnastics.
Methods

Four competitive (national level) female gymnasts (mean ± SD age: 20 ± 0.8 years, height: 1.64 ± 0.08 m, body mass: 59.0 ± 6.9 kg), who were injury-free and in current training of an average of 20 hours a week were recruited for the study. The experimental protocols were approved by the University’s Research Ethics Committee and written informed consent was provided by the gymnasts prior to participation in the study. The approved protocol required each gymnast to perform 10 backward rotating somersault dismounts from beam in a pike and tuck position (N = two x 10 dismount trials for each gymnast). The gymnasts were instructed to perform well-executed dismounts from the beam using a safe and aesthetic landing style. All dismounts were qualitatively judged according to the Fédération Internationale de Gymnastique Code of Points by a national-level coach.

Seven active markers were located unilaterally on the right side of each gymnast prior to the execution of the dismount trials. Markers were superficially attached to the metatarsalphalangeal (mtp), ankle, knee, hip and shoulder joint centres (Figure 2) to obtain lower body joint kinematic profiles. Markers were additionally located on the elbow and wrist joint centres to assist the determination of planar, whole body mass centre (CM) motion during the dismount trials. The active markers were automatically tracked (sample rate of 200 Hz) for the duration of each dismount trial using two co-aligned Cartesian Optoelectronic Dynamic Anthropometer (CODA 6.30B-CX1) motion analysis scanners (Charnwood Dynamics Ltd., Leicestershire, UK).

Two-dimensional, sagittal plane (z: vertical, y: anterior-posterior) coordinate data were low-passed filtered at a 10 Hz cut-off frequency, which was determined using Winter’s residual analysis. The early landing or impact phase (Figure 1), was defined for the dismount trials using the filtered mtp coordinate data. The onset of the impact phase was established at mtp touchdown (TD) when the z-displacement of the respective active marker
descended below the pre-measured unloaded landing surface height of the ground. The instant at which a stable, loaded mtp z-displacement on the ground was achieved by the gymnast defined the completion of the impact phase. The maintenance of a mtp z-displacement of less than a 3 mm deviation in the mean loaded ground position, recorded over a 1 s duration prior to the dismount skill being executed defined the respective stable, loaded position. As detailed by Gittoes et al.\textsuperscript{10}, the use of the mtp marker displacement for identifying the temporal characteristics of the impact phase was evaluated by comparing the derived touchdown time with the corresponding time obtained using force plate data. A mean ±SD difference of $0.003 ± 0.004$ s was achieved between the kinematic and kinetic definitions of the TD time.

Sagittal plane kinematic profiles for the whole body, and ankle, knee and hip joints were defined using the filtered coordinate data of the impact phase. Each gymnast’s CM location was derived relative to the global origin (centre of the force plate) using a segmental analysis, which combined gymnast-specific segmental inertia profiles with the proximal and distal joint centre coordinate data of the respective segments. Gymnast-specific inertia profiles were established using height and whole body mass scaled to the inertia profiles of 30 national-level female gymnasts, which were determined using direct measurements and Yeadon’s inertia model\textsuperscript{16}. The whole body kinematic landing strategy used by each gymnast in the impact phase was subsequently characterised by the CM $z$- and $y$-displacement and velocity at TD, the whole body orientation at TD, and the maximum $z$-displacement achieved by the CM during the impact phase (maximum squat height). Whole body orientation, which is further defined in Figure 2, was established as the angle formed between the global forward progression horizontal vector ($y$-axis) and the mtp joint to CM vector. The sagittal plane ankle, knee and hip joint angles were defined as the angle formed between co-aligned segments (e.g. foot, shank, thigh or upper body) forming the respective joint.
Continuous profiles and discrete measures of the joint angular displacement and angular velocity profiles defined the local joint kinematic strategy employed in each dismount trial. The trial-specific time profiles were interpolated to 100 points and normalized to 100% of the respective impact phase. The discrete measures included the ratio of the maximum knee and hip joint flexion angular displacement in the impact phase, which was previously used\(^3\) to quantify strategy bias. A ratio of less than one indicated a knee-biased landing strategy while a ratio exceeding one indicated the use of a hip-biased landing strategy.

Tests of normality were conducted on the discrete whole body and joint kinematic measures prior to the application of a univariate repeated measures t-test (two-tailed). A conservative alpha level of .01 was selected for the t-test analyses. The respective analyses were employed to examine skill differences in the kinematic landing strategies used by individual gymnasts (N = 10 pike versus 10 tuck trials) and the group (N = 40 pike versus 40 tuck trials).

The individual gymnast and group ensemble joint kinematic time histories were determined as the average across each time point for the individual gymnast trials (N = 10 trials for each skill) and all gymnast profiles (N = 40 trials for each skill), respectively. Skill differences in the ankle, knee and hip joint kinematic profiles were quantified as the root mean squared difference (RMSD) between ensemble pike and tuck time histories. The RMSD was further presented as a percentage of the range in the ensemble tuck kinematic profile. The individual gymnast and group range in the tuck profile kinematic measures were determined from the individual gymnast and group derived ensemble profiles, respectively.
Results

Each gymnast and the group executed the pike and tuck skills using similar impact phase durations regardless of the existence of a less rapid horizontal (group skill difference: -0.07 m.s\(^{-1}\), \(p < .01\)) and CM \(z\)-velocity at TD (group skill difference: -0.14 m.s\(^{-1}\), \(p < .01\)) in the pike skill (Figure 3). While the group simultaneously executed the pike skill with a lower CM \(z\)-displacement at TD compared to the tuck skill (group skill difference:-0.03 m, \(p < .01\)), similar maximum CM \(z\)-displacement were achieved between skills later in the impact phase. Similarities in the strategy bias used in the pike (group mean ± SD 1.56 ± 0.26) and tuck (group mean ± SD 1.57 ± 0.33) skill were also evident and supported the typical regularity in the individual knee and hip joint maximum flexion angular displacements employed by each gymnast (gymnasts 1, 2 and 4).

While similar maximum joint flexion angular displacements were found between skills for individual gymnasts and the group, gymnast-specific adaptations to the joint kinematics strategies used at TD (Figure 4) were evident between skills. Compared to the tuck skill, Gymnast 1 and Gymnast 4 used a less \((p < .01)\) extended hip joint position at TD in the pike skill while Gymnast 3 preferred a more \((p < .01)\) plantar-flexed ankle and flexed knee joint, respectively at TD. Gymnast 2 conversely employed a more rapid \((p < .01)\) hip joint angular velocity at TD in the pike \((2.5 ± 0.6 \text{ rad.s}^{-1})\) compared to the tuck skill \((1.0 ± 0.9 \text{ rad.s}^{-1})\).

Skill differences in the joint angular displacement profiles (Figure 5) of the ankle, knee and hip were demonstrated across the impact phase duration. The RMSD between the pike and tuck angular displacement profiles was typically lowest across gymnasts for the ankle (group RMSD: 10.9%) when compared to the knee (group RMSD: 19.8%) and hip (group RMSD: 17.9%). The RMSD in the joint angular velocity profiles for each gymnast
and the group were however typically more prominent for the hip joint (group RMSD: 30.9%) when compared to the ankle (group RMSD: 13.6%) and knee (group RMSD: 15.4%)

**Discussion**

The individual and group kinematic landing strategies used by four gymnasts performing backward rotating pike and tuck somersault dismounts were examined to gain insight into strategy transference in fundamental dismount skills. While the whole body kinematic strategy was regulated between skills, individual gymnast joint kinematic strategies were preferred to accommodate the skill-specific initial velocity conditions of the dismounts. Skill discrepancies in the height and z-velocity of the CM at TD were evident for individual gymnasts and across all gymnasts, and were considered indicative of the marginally diverse preceding aerial phase requirements of each skill. The more rapid CM velocity at TD of the tuck compared to the pike skill was explained by a higher preceding landing height (group mean ± SD tuck: 2.180 ± 0.047 m, pike: 2.224 ± 0.030 m) in the respective skill, which was evidenced in a prior investigation examining the aerial phase responses of the same gymnasts and trials10. Takei and Dunn17 previously supported the achievement of a higher peak of flight in backward rotating dismounts requiring a more tucked position in flight following group analyses.

A more rapid horizontal velocity of the CM at TD was also evident in the group analyses for the tuck compared to the pike skill. Sheets and Hubbard18 has previously suggested a larger CM horizontal velocity just prior to impact during a double somersault dismount that required a higher flight height when compared to its single somersault counterpart. As evidenced by the similar whole body orientations achieved by each gymnast and the group, the larger linear impulses generated by the more rapid CM velocity at TD in the tuck compared to the pike skill were attenuated using a consistent whole body angular
configuration. Regardless of the diverse impact velocity conditions of the fundamental dismount skills, the maximum CM z-displacement (squat height) and duration of the subsequent impact phase were also regulated between skills by each gymnast and the group. Self-regulation of the whole body kinematic strategy employed for the impact phase duration, despite different preceding whole body CM kinematics at TD, may be indicative of technical proficiency and effective transference of the kinematic strategy between the fundamental dismount skills. Since whole body orientation responses made during the impact phase were typically comparable between skills for the individual gymnasts and group, adjustments to the differing CM conditions at TD and the maintenance of the squat height were potentially explained by localised joint compensations.

Skill differences in the joint kinematic measures were specific to individual gymnasts and joints. Transference of the landing strategy between the dismount skills may therefore require a local kinematic response customised to the individual gymnast rather than the task in order to maintain a successful and safe dismount. The lower RMSD between skills in the ankle compared to the knee and hip joint angular displacement profiles suggested a restriction in the extent to which all gymnasts could accommodate the more rapid impact velocities of the tuck compared to the pike skill through ankle joint configuration adaptations. In contrast, the typically larger RMSD for the hip compared to the knee and ankle joint angular velocity profiles suggested a tendency for the use of modified hip motions to compensate the diverse linear momentum reduction demands. The lack of consistent skill differences in the discrete kinematic measures for the hip joint across the group however suggested a self-regulation in the extent and timing of the hip joint kinematic changes achieved in the impact phase. While individual gymnast regulation of the hip joint motion was achieved in the kinematic landing strategies employed between skills, a similar hip-biased strategy was selected by all gymnasts for the skills (group mean ± SD tuck: 1.56±0.26, pike: 1.57±0.33). The maintenance of a
common strategy bias by gymnasts performing drop landing tasks on diverse surfaces was previously reported. The use of a stable strategy bias during ground contact may subsequently provide an important indicator of landing strategy mastery and effective skill transference in velocity-controlled and more complex gymnastic-style landing tasks. Investigations of landing mechanics have typically examined individual joint analyses. The identification of a common strategy bias in the respective study provides support for further consideration of the joint coordination actions in extending insight into strategies employed to regulate impact phase responses (e.g. phase duration and squat height) in fundamental gymnastic landing tasks.

Takei and Dunn highlighted that the identification of mechanical indicators of fundamental dismounts may be helpful in developing the mechanical foundation necessary for learning more advanced dismounts. The stabilisation of the whole body orientation and strategy bias in the landing strategies examined in this study may accordingly provide important biomechanical indicators for the execution of fundamental dismount routines, and the development of more advanced dismounts. The gymnast- and joint-specific modifications to the individual joint strategies were potentially indicative of functional adaptations necessary to accommodate the skill-specific impact velocity conditions between dismount skills. As suggested by McNitt-Gray et al., modifications to the landing strategy may be functional in allowing gymnasts to perform landing tasks under diverse conditions. The extent to which joint kinematic strategies were diversely modified by individual gymnasts between skills may partially be attributed to discrepancies in individual expertise. As proposed by the theory of Bardy and Laurent, inconsistency in the strategy used between conditions may be indicative of less expert performance. Gymnastic-specific adjustments to the lower limb joint kinematic pattern used in dismounting have more explicitly been associated with dismount scores. The individualised joint strategy adaptations made between
skills within this investigation may therefore partially be explained by varying levels of gymnast’s expertise and performance. Further cross-sectional investigations examining strategy modifications and dismount performance in association with expertise level are however warranted to support an explanation for the individual responses.

Unlike traditional studies, which have typically investigated group responses between landing conditions, simultaneous individual performer and group analyses were conducted in this study to provide insight into the idiosyncratic and generic requirements for skill transference. The success of the dismount trials, and the physical characteristics and experience of the gymnasts were not explicitly considered within this investigation. The inclusion of a between-gymnast and matched group analyses in future investigations may subsequently be warranted to allow insight into the influence of physical characteristics and performance level on the selection of landing strategies. The identification of common components of the kinematic landing strategy used by gymnasts in dismount skills may further be important in informing potential rule changes centred on alleviating the physical demands of dismounting. For example, the use of a regulated whole body orientation at TD may suggest that the respective component is an essential element of the dismount that should be maintained within the scoring system.

In conclusion, kinematic landing strategies employed to successfully execute backward rotating dismount skills may be indicated by the use of a common whole body orientation and knee-hip strategy bias during ground contact. Self-regulation of the individual joint kinematic responses may however be necessary to successfully achieve landing strategy transference between dismount skills. The effective mastery of dismount skills may benefit from consideration of the individual and coordinated joint strategy adjustments made in accordance to the gymnast’s performance level.
References


Figure 1 - Schematic representation of the aerial and impact phase of the backward rotating (a) pike and (b) tuck dismount skill. Whole body orientation is indicated by the vector (thick line) formed between the CM (●) and metatarsalphalangeal joint location.
Figure 2 - Schematic representation of the marker placement protocol used in the data collections. The whole body orientation (θ) and joint angle configurations (ρ) are exemplified for the instant of touchdown of a dismount trial.
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![Graph a)
Phase Duration (s)

Gymnast

Group

![Graph b)
Strategy Bias

Gymnast

Group


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Figure 3 - Discrete whole body kinematic measures of the impact phase of backward rotating pike (white) and tuck (black) somersaults from beam. a) phase duration; b) strategy bias; c) CM z- and y-displacement at TD; d) CM z- and y-velocity at TD; e) CM maximum z-displacement; f) whole body orientation at TD. (*significant difference at $p<0.01$, two-tailed t-test).
Figure 4 - Discrete lower body joint kinematic measures of the impact phase of backward rotating pike (white) and tuck (black) somersaults from beam. a) joint angular displacement at TD; b) joint angular velocity at TD; c) maximum joint flexion angular displacement; d) peak joint flexion angular velocity; e) range of joint angular displacement. (*significant difference at $p < .01$, two-tailed t-test).
Figure 5 - Root mean squared differences (RMSD) between individual gymnast and group ensemble ankle (white), knee (black) and hip (textured) a) angular displacement and b) velocity time profiles for the impact phase of backward rotating pike and tuck somersaults. RMSD are presented as a percentage (%) of the range in the respective tuck profile.