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Which typical floor movements of men's artistic gymnastics result in the most extreme lumbar lordosis and ground reaction forces?

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Back pain is prevalent among gymnast populations and extreme flexion or extension of the lumbar spine along with high ground reaction forces (GRFs) are known to increase intervertebral stress. The aim of this study was to determine which postures and dynamic conditions among common floor movements provide the greatest risk of injury in men's artistic gymnastics (MAG). For this purpose, lumbar spine curvatures, obtained through a full-body subject-specific kinematic model fed by motion capture data, and GRFs on feet and hands were compared between typical floor movements of MAG (*pike jump, round off back handspring, front handspring, forward* and *backward tucked somersaults*) performed by six adolescent gymnasts. The *round off back handspring* and the *pike jump* resulted respectively in the largest lumbar extension and flexion, and the *forward tucked somersault* take-off in the highest GRF. At ground impacts, the largest lumbar flexion was during the *backward tucked somersault* landing and only the *back handspring* hands ground contact phase led to lumbar extension. Such identification of high-risk conditions should enable better back pain management in gymnastics through more tailored training adaptations, particularly in case of pathologies or musculoskeletal specificities.

Keywords: gymnastics; lumbar; spine; kinematics; impacts

Introduction

Artistic gymnastics is a very popular sport. However, gymnasts are at major risk of low back pain, with a 12-months prevalence of 73%-88% (Wilson et al., 2021), which is the second most common pathology in gymnastics (20% of diagnosis) after tendinopathy (32%) (Paxinos et al., 2019). Furthermore, previous studies have shown that 57% of injuries are overuse injuries (Paxinos et al., 2019), showing the risk associated with the frequent repetition of movements placing high stress on the lumbar spine. Previous studies have also shown that the floor is the apparatus with the highest injury prevalence in male artistic gymnastics (MAG) (Goulart et al., 2016; Kruse & Lemmen, 2009), involving both lower and upper extremity impacts as well as frequent hyperextensions and hyperflexions of the spine.

Large forces generated during take-off, rebounding and landing are transmitted along the spine, which is all the more stressed when it is in hyperflexion or hyperextension (Kruse & Lemmen, 2009). The repetition of stressful movements, which alternatively stress the spine in flexion and in extension, leads successively to traction and compression forces at the level of the articular apophyses which is a risk factor for isthmic lysis and spondylolisthesis (Adams, 2004; De Jonge & Kramer, 2014; Kruse & Lemmen, 2009). In addition, forces are transmitted through vertebral bodies thanks to intervertebral discs (IVDs), which evenly distribute the forces on the vertebral bodies (Adams, 2004). But the repetition of compression forces can lead to micro-fractures, mostly at vertebral endplates or even to fractures (Adams, 2004) and shear forces within IVDs may also result in progressive IVD degeneration (De Jonge & Kramer, 2014; Kruse & Lemmen, 2009; Xia et al., 2015).

The impacts and long-term effects of low back pain for gymnasts are of great concern as it can lead to training interruption, an end to the practice or even life-long disabilities (Maffulli et al., 2010). Therefore, back pain prevention in gymnastics is crucial to maintain the health of the gymnasts. By informing gymnastics coaches and medical staff of dynamic conditions that particularly stress the lumbar spine, they would be better able to adapt the training to prevent injury or to deal with gymnasts who have musculoskeletal specificities or being in rehabilitation program after injuries. To this aim, a good knowledge of postures and movements that are more prone to stress the lumbar spine is needed.

Unfortunately, it is not possible to make direct measurements of the loading of IVDs and apophyseal joints during movements. Therefore, other indicators of intervertebral contact forces are needed. As extreme flexion and extension of the lumbar spine and high ground reaction forces (GRFs) are known to increase stress in the lumbar spine (D’Hemecourt & Luke, 2012; Hall, 1986; Sonvico et al., 2019; Wade et al., 2012), these parameters can be considered as good indicators of the level of intervertebral stress that could occur. In addition, extreme lumbar extension or flexion associated with high loads further increases the stress in the lumbar spine (Hall, 1986; Sonvico et al., 2019; Wade et al., 2012). Particularly, high GRFs during landing or take-off may result in hyper-pressure in the IVDs and significant shear forces if the lumbar spine curvature is such that it already pinches IVDs and if the spine is not stabilized through a correct activation of the erector spinae and the abdominal muscles(Sonvico et al., 2019; Tavakoli & Costi, 2018; Wade et al., 2012).Therefore, the posture of the lumbar spine in terms of flexion/extension at the instances of peak GRFs can also be considered as an indicator of the risk of injury during gymnastic movements. Even if previous studies have already quantified the spine flexion-extension range of motion during static postures (Sonvico et al., 2019) or during women's artistic gymnastics (WAG) movements (*back walkover* and *back handspring*) (Pimentel et al., 2020), it seems that none have quantified lumbar lordosis values during MAG movements.

The aim of the study was therefore to determine in five typical floor movements of MAG (*pike jump, round off back handspring, front handspring, forward* and *backward tucked somersaults*): *i*) the ranges of flexion and extension of the lumbar spine, *ii*) the peak GRFs at the hands and feet, and *iii*) the posture of the lumbar spine in terms of flexion/extension at the instances of peak GRFs. It is hypothesised that the five MAG movements investigated lead to significant differences in *i*, *ii* and *iii* that enable identification of the movements that are the most demanding for the lumbar spine.

Materials and methods

Participants

After receiving ethical agreement for the study (ID RCP: 2018-A01926-49), six young MAG athletes (referred to as MAG 1 to MAG 6 in this article) who trained more than fifteen hours per week in the same training institution and were involved in national level competitions consented to participate in the study. Gymnasts were 13 years old on average (range: 12 to 14 years old). Their masses were 44.5 ±6.7 kg (range: 35.0 kg to 52.8 kg) and their heights were 1.53 ±0.08 m (range: 1.43 to 1.62 m).

Data collection

Gymnasts underwent a motion capture session that took place in a motion analysis lab. The lab was equipped with a dedicated instrumented gymnastic floor (plywood floor covered with a carpet and mounted on foam blocks) allowing GRFs to be measured through four force-plates (AMTI, 1000 Hz) placed under the gymnastic floor (Figure 1, A). Eighty-two reflective markers were placed on the segments of the gymnasts: 38 on their lower limbs, five on their pelvis, four on the spine (L5, T12, T8 and C7), and the thirty-five others on the upper limbs and the thorax (Figure1, B and C). The three-dimensional location of the markers was tracked at 200 Hz by a 14-cameras optoelectronic motion capture system (Vicon system, hardware: 1.3/2.2 Vero cameras; Nexus 2 software; Oxford Metrics, UK). For each gymnast, a static acquisition in upright standing posture was done (Figure 1, B). Then, common MAG movements were performed (Figure1, A). Skills to investigate were previously selected based on coaches and medical staff perception of the skills that require spine hyperflexion or hyperextension as well as high impacts. Gymnastics skills should be executed without fall, and lower and upper extremities being on the appropriate force-plates. Each gymnast repeated movements he was confident with, resulting in at least three *pike jumps*, five *rounds off back handsprings*, three *forward tucked somersaults*, two *backward tucked somersaults* and two *front handsprings* usable for the analysis for each gymnast. Only four participants succeeded to perform the *backward tucked somersault* and five the *forward tucked somersault*.

Figure 1. Photographs during experimental sessions: (A) Back handspring execution in the motion analysis lab equipped with four force-plates (delimited by red lines on the image), (B) Static acquisition in upright standing posture, (B & C) Set of reflective markers in anterior and posterior views, (D) Biplanar radiographic acquisitions in neutral standing upright posture with retro-projected

reconstructions in red, (E) EOS system, (F) Pelvis and vertebral geometries from pelvis and vertebrae 3D-reconstructions.

After the motion capture acquisitions, gymnasts underwent micro-dose biplanar radiographs (EOS system, EOS imaging, France) for biomechanical model personalisation purposes. Radiographs were made in the EOS recommended neutral standing upright posture, while still being equipped with the reflective markers of the motion capture system (Figure 1, E).

Full-body model

As 3D kinematics of the spine during gymnastic movements cannot be determined directly from the motion capture data, a kinematic model should be used. Therefore, a three-dimensional linked-segment full-body model has been developed using the open-source musculoskeletal simulation software OpenSim (Delp et al., 2007) and allowed to assess the lumbar spine curvature during gymnastic movements. The lumbar spine curvature, also called lumbar lordosis, was defined as the angle between the sacral endplate and the vertebral body orientation in the sagittal plane of the first lumbar vertebra.

The model was based on the full-body model of Raabe and Chaudhari (Raabe & Chaudhari, 2016) with a spine kinematic chain based on the model of Bruno et al (Bruno et al., 2015). Intervertebral joints frames were set to be colinear and intervertebral joints centre were located in the middle of the IVDs. However, in the model of Bruno et al (Bruno et al., 2015), the intervertebral joints motions of the whole lumbar and thoracic spine segments (i.e. from S1/L5 to T2/T1) are linearly constrained in flexion-extension, lateral deviation and axial rotation by three S1/L5 generalized coordinates. Therefore, the kinematic constraints coefficients described in Bruno et al. (Bruno et al., 2015) were re-expressed so as to distinguish between the lumbar (S1/L5 generalised coordinate) and thoracic (L1/T12 generalised coordinate) sections in order to keep these two sections kinematically independent, as it was done by Christophy et al (Christophy et al., 2012). A body-specific coordinate system was defined for each vertebra in order to calculate directly the angles between S1 and L1 vertebrae (with *z-x'-y''* rotation sequence, corresponding to flexion/extension then lateral bending then axial rotation) and to determine the global lumbar flexion-extension angle (first angle of the rotation sequence).

This generic model was then scaled to each gymnast through proportional coefficients based on distances between specific markers. The resulting models were also personalised to each participant in terms of pelvis and vertebrae geometries along with intervertebral joint centres locations. This was done on the basis of pelvis and vertebrae 3D-reconstructions made from the biplanar radiographic acquisitions (Dubousset et al., 2005; Humbert et al., 2008)(Figure 1, D and F).

Location of the markers placed on the pelvis, the spine and the thorax was also personalised from imagery data, as done previously for the lower limbs (Assi et al., 2016; Puchaud et al., 2020; Sauret et al., 2016).

Data processing and analysis

Joints kinematics during MAG movements was determined using a multibody kinematics optimization algorithm implemented in OpenSim 3.3 software, allowing the time courses of all the model generalized coordinates to be determined. Bodies kinematics was then calculated from inverse kinematics results in order to get position and orientation of each body of the model during movements.

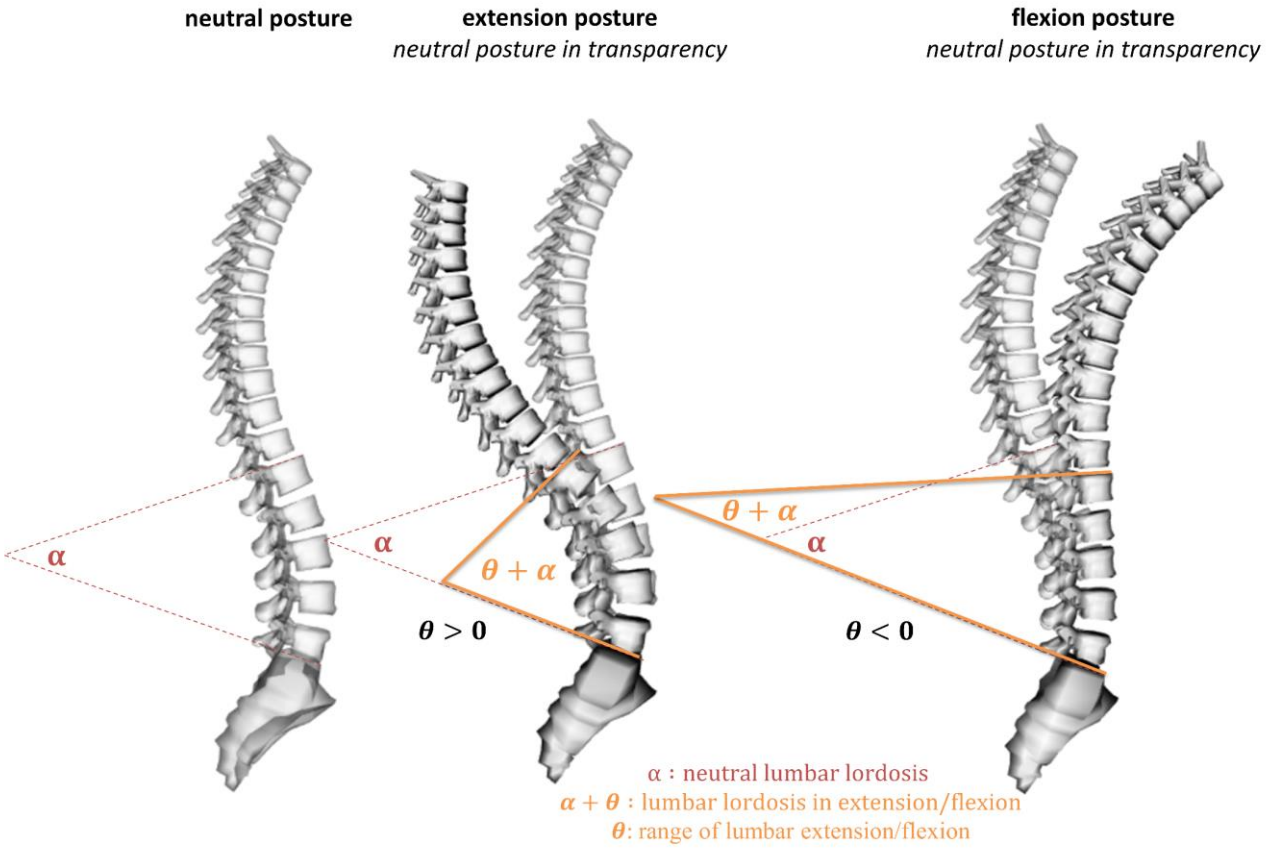

Figure 2. Schematic representation of the neutral posture along with the extension and flexion postures of the lumbar spine and associated angles calculated during the analysis.

The neutral lumbar lordosis (angle $\propto$ on Figure 2) of each gymnast was calculated from the 3D-reconstructions made from the biplanar radiographic acquisitions of the participants taken in natural standing posture. For each gymnast, the time courses of the lumbar lordosis, averaged over the different repetitions of each movement, were calculated from body kinematics. Then, the extension and flexion angles (angle θ on Figure 2) of the lumbar spine over time were also calculated for each gymnast by subtracting the neutral lumbar lordosis (i.e. $\propto$) from the calculated instantaneous lumbar lordosis. Hence, a positive angle value indicated a lumbar extension posture and a negative value indicated a lumbar flexion posture. The flexion-extension (FE) range of motion (ROM) of a movement was defined as the amplitude between the maximum of flexion and the maximum of extension within each movement.

Data from force-plates were retrieved to calculate peak GRFs on feet and/or hands for each acquisition. Only the most significant GRFs were analysed. Therefore, the landings of the *pike jump*, the *front handspring*, the *forward* and *backward tucked somersaults* were examined. The *back handspring* and *forward tucked somersault* take-off and also the hands ground contact phases of the *front* and *back handspring* were also analysed. GRFs were decomposed into a vertical component (perpendicular to the floor pointing upward), and an antero-posterior component (main direction of the movement). Values were then normalized in term of body weight (BW) and averaged over the different repetitions of each movement for each gymnast. Instances of peak GRFs were also regarded for the analysis of the lumbar spine curvature at ground impacts.

Given the sample size, individual outcomes are considered first for the study of the FE movements of the lumbar spine over movements. In view of the similar behavior observed between the gymnasts, averages and standard deviations over the six participants were then calculated as for maximum of lumbar flexion/extension, FE ROM, GRFs and lumbar flexion/extension angles at peak GRFs.

Regarding statistics, still with respect to the low number of participants, non-parametric statistical tests for paired data of Wilcoxon (rank sum test) were conducted using the R software (R 4.2.0, R Core Team). The significance level was chosen at $\alpha=0.05$ and every probability (p-values) was reported as well as the effect sizes (r). Effect sizes are considered small if $r < 0.3$, moderate if $0.3 \leq r < 0.5$ and large if $r \geq 0.5$. In the results section, for readability purpose, only differences for which *p*-values are lower than 0.05 and effect sizes are large were specified.

Results

MAG movements performed are illustrated in figure 3, which shows also the main events considered further in the analysis. Results describe first the FE movements of the lumbar spine during MAG movements and compare movements in terms of maximum of lumbar flexion and extension. In a second part, results focus on peak GRFs and on the values of lumbar flexion or extension at the instances of peak GRFs.

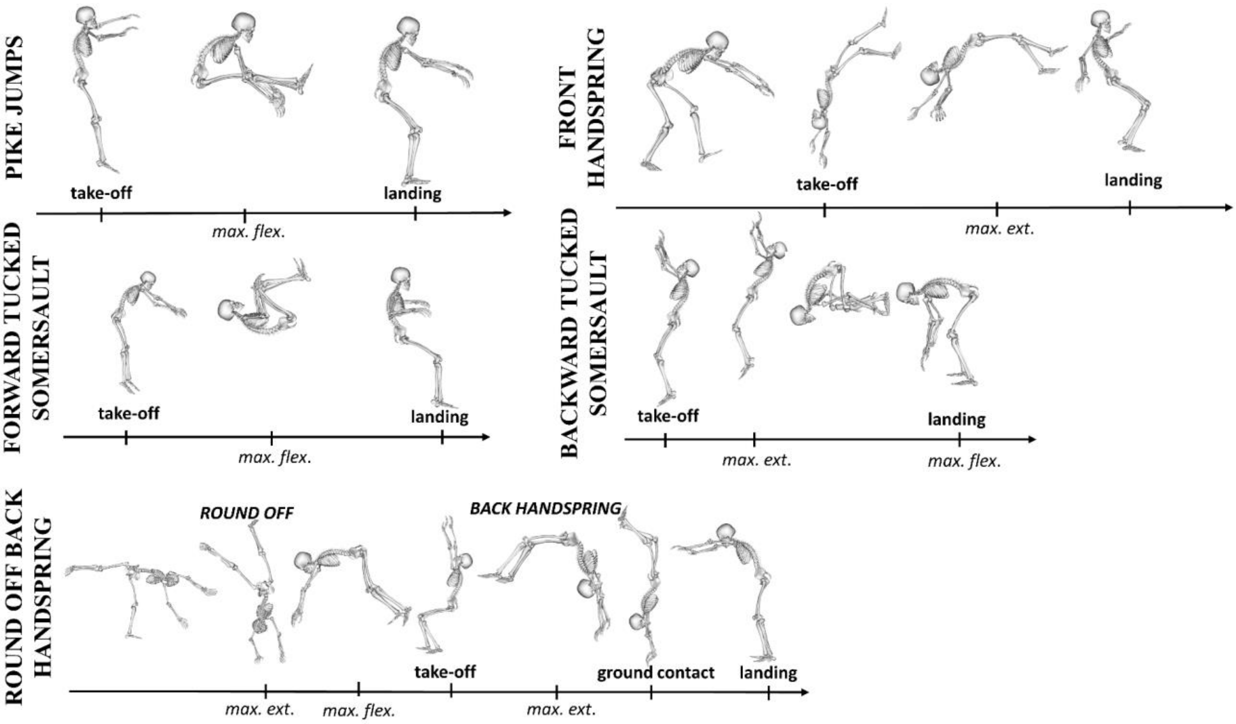

Figure 3. Illustration of the 6 MAG movements studied showing the main events considered further in the analysis.

Population description

Neutral lumbar lordosis values of the gymnasts ranged from 51° to 78° with an average value of 63°±10° (66°, 78°, 61°, 56°, 69°, 51°, for participants 1 to 6, respectively).

Lumbar lordosis

MAG movements description

Figure 4 depicts the instantaneous angle of FE of the lumbar spine with reference to neutral lumbar lordosis (i.e. θ) for each participant and for each movement. Even if differences in terms of strategies of flexion and extension of the lumbar spine during movements could be observed based on the curves, comparable trends were found between the gymnasts and enabled to characterize each movement in term of FE movements of the lumbar spine. Hence, movements are described below.

Pike jumps started with a take-off during which gymnasts flexed and then extended their lumbar spine. During the jump, gymnasts raised their legs while flexing their lumbar spine up to a maximum of lumbar flexion ($|\theta| = 80°\pm13°$ on average, resulting from a mean lumbar lordosis ($\theta+\propto$) of -17°±10°). Next, during the descending phase of the jump, gymnasts extended their lumbar spine while they straightened. At landing, they flexed their lumbar spine.

At the start of *rounds off*, gymnasts extended their lumbar spine up to a maximum of extension (θ=18°±14° on average, resulting from a mean lumbar lordosis (θ+∝) of 80°±15°) reached during the handstand. Next, gymnast flexed their lumbar spine up to the second take-off that engaged the *back handspring* and a lumbar extension up to a second maximum (30°±11° on average, resulting from a mean lumbar lordosis of 92°±12°) reached before the hands impacted the ground. Gymnasts flexed then their spine to support the landing.

At the start of *front handsprings* gymnasts extended their lumbar spine up to a maximum of extension (9°±6° on average, resulting from a mean lumbar lordosis of 72°±10°). Then, during the descending phase of the movement, gymnasts flexed their lumbar spine to support the landing.

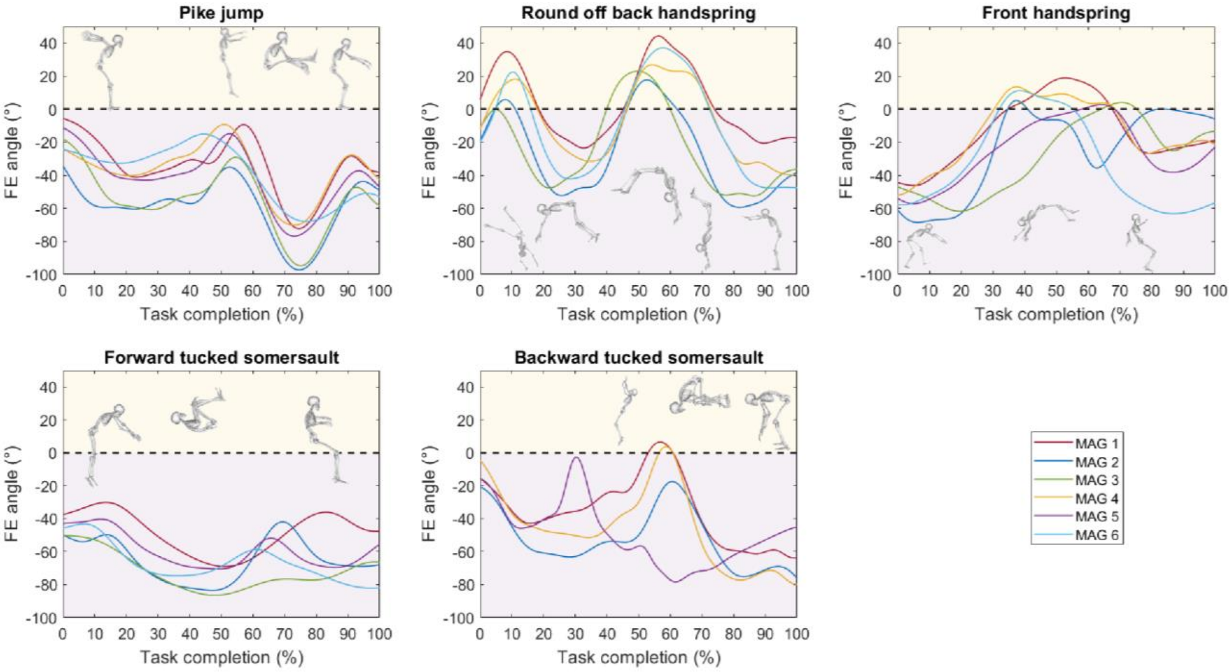

Figure 4. FE movements of the lumbar spine with reference to the neutral position, averaged over the repetitions of each movement for each gymnast. A positive (respectively negative) FE angle indicates the lumbar spine is in an extension (respectively flexion) posture. An increase (respectively decrease) of the FE angle shows the lumbar spine is extending (respectively flexing).

After the take-off of *forward tucked somersault*, gymnasts flexed their lumbar spine in order to reach the tucked posture (78°±8° of lumbar flexion on average, resulting from a mean lumbar lordosis of -14°±12°). During the descending phase, the gymnasts straightened and extended their lumbar spine while staying in a lumbar flexion posture with reference to the neutral posture. At landing, the gymnasts flexed again their lumbar spine.

Backward tucked somersault started with a take-off during which gymnasts made a flexion-extension movement of the lumbar spine up to reach a maximum of extension (mean lumbar lordosis of 64°±7°). The gymnasts then flexed their lumbar spine to reach the tucked position. Landing was preceded by a slight straightening of the lumbar spine and at ground impact gymnasts flexed their lumbar spine.

MAG movements comparison

In terms of FE ROM (Figure 5), the movements involving the lumbar spine the most were the *round off back handspring* and the *backward tucked somersault* (77°±7° and 77°±6° respectively) followed by the *front handspring* and the *pike jump* (68°±6° and 67°±9° respectively) and then, the *forward tucked somersault* (39°±5°). In terms of lumbar extension, the most demanding movement was the *round off back handspring* (30°±11°), followed by the *front handspring* (9°±6°) while the *pike jump* and the *forward tucked somersault* only involved the lumbar spine in flexion. Finally, the *pike jump* (80°±13°), the *backward tucked somersault* (79°±11°) and the *forward tucked somersault* (78°±8°), required almost the same level of lumbar flexion while the *front handspring* (59°±8°) and the *round off back handspring* (47°±12°) required less lumbar flexion.

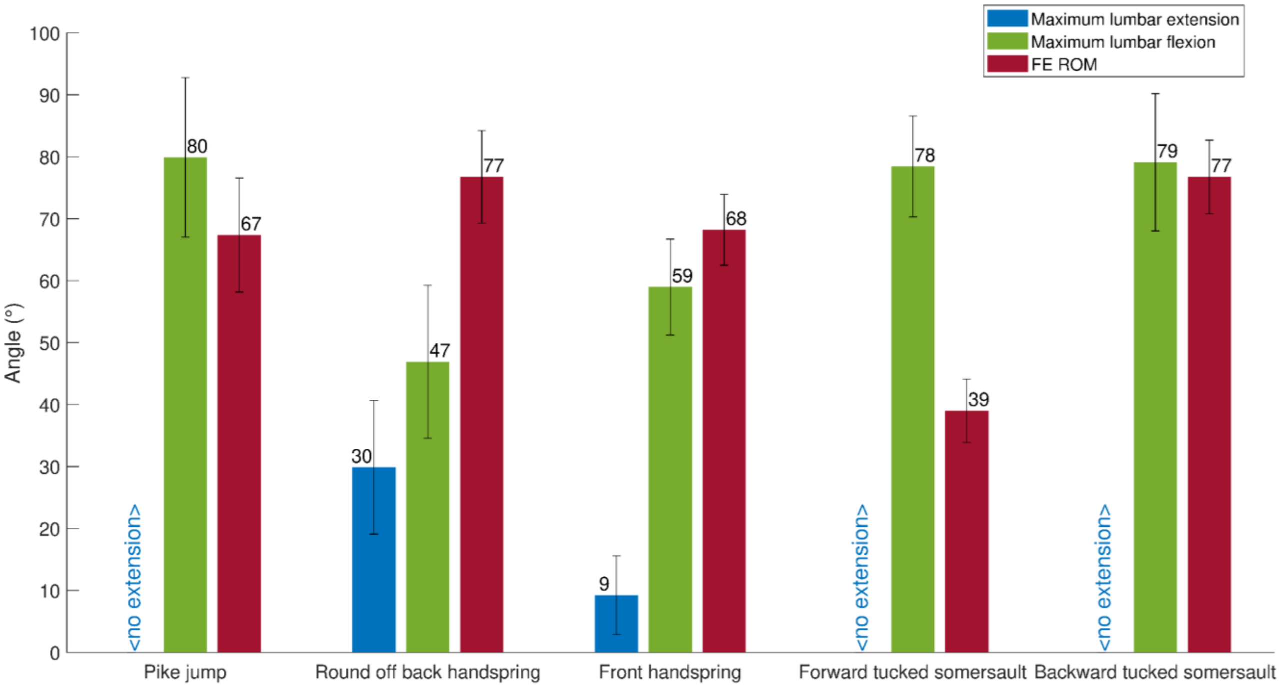

Figure 5. Maximum lumbar flexion, extension and FE ROM averaged over all participants for each movement.

Regarding statistics, the only difference that was found to be significant was between the range of flexion of the *pike jump* and the *front handspring* (p=0.03). All p-values and associated effect sizes are reported in supplementary materials (Tables S1 to S3).

Ground reaction forces

The vertical (respectively antero-posterior) component of peak GRFs accounted on average for 98 % (respectively 1 %) of the total force for landings on feet, 94 % (respectively 6 %) for take-off on feet, and 95 % (respectively 5 %) for hands ground contact phases. Therefore, GRFs are mainly vertical and antero-posterior. Peak total, vertical and antero-posterior GRFs of studied ground impacts are reported in figure 6. In addition, the reader must be aware that instances of peak vertical GRFs matched instances of peak total GRFs except for 5 % of the trials (with desynchronisation ranging from 5 to 10 ms) but higher desynchronisation was observed between peak total and antero-posterior GRFs in 86 % of trials, ranging from 5 to 90 ms.

Maximum ground reaction forces

Greatest total GRF was reached during the *forward tucked somersault* take-off with peak GRF of 10.1±0.9 ×BW. Peak total GRFs higher than five times the body weight were also reached during landings on both feet of the *forward tucked somersault (*7.2±0.7×BW), the *backward tucked somersault (*7.1±2.1×BW), the *front handspring (*6.4±1.2×BW) and the *pike jump (*6.2±1.1×BW). The *back handspring* take-off –following the *round off*– exhibited smaller total GRFs of 4.1±0.5 ×BW on average. Finally, peak total GRFs during the hands ground contact phases of the *back (*3.0±0.7×BW) and *front handsprings (*2.8±0.4 ×BW) were smaller than those of all feet impacts analyzed and previously stated.

Considering vertical GRFs only, results were similar to those found when considering total GRFs, amplitudes being slightly lower (Figure 6). Considering antero-posterior GRFs, greatest force was also reached during the *forward tucked somersault* take-off (2.5±0.6 ×BW). Other impacts led to antero-posterior GRFs of the order of 1×BW, except for hands ground contact phase of the *back handspring* that was weaker (0.2±0.1 ×BW) (Figure 6).

Regarding statistics, the *back handspring* take-off resulted in significantly lower total GRFs than both the *pike jump* landing (*p*=0.03) and the *front handspring* landing (*p*=0.03). During the two hands ground contact phases analysed (*back handspring* and *front handspring*), total GRFs were significantly lower than during take-off and landing on feet (*pike jump* landing, *back handspring* take-off and the *front handspring* landing) (*p*=0.03 in all of these cases). In terms of vertical GRFs, differences which turned out to be significant were the same (and with same p-values) with the exception of the difference between the *back handspring* take-off and hands ground contact phase that was just above the significant threshold (*p*=0.06). In terms of antero-posterior GRFs, the hands ground contact phase of the *back handspring* resulted in significantly lower antero-posterior GRFs than during both the *pike jump* landing, the *back handspring* take-off, the *front handspring* landing and also the hands ground contact phase of the *front handspring* (p=0.03 for all). All p-values and associated effect sizes are reported in supplementary materials (Tables S4 to S6).

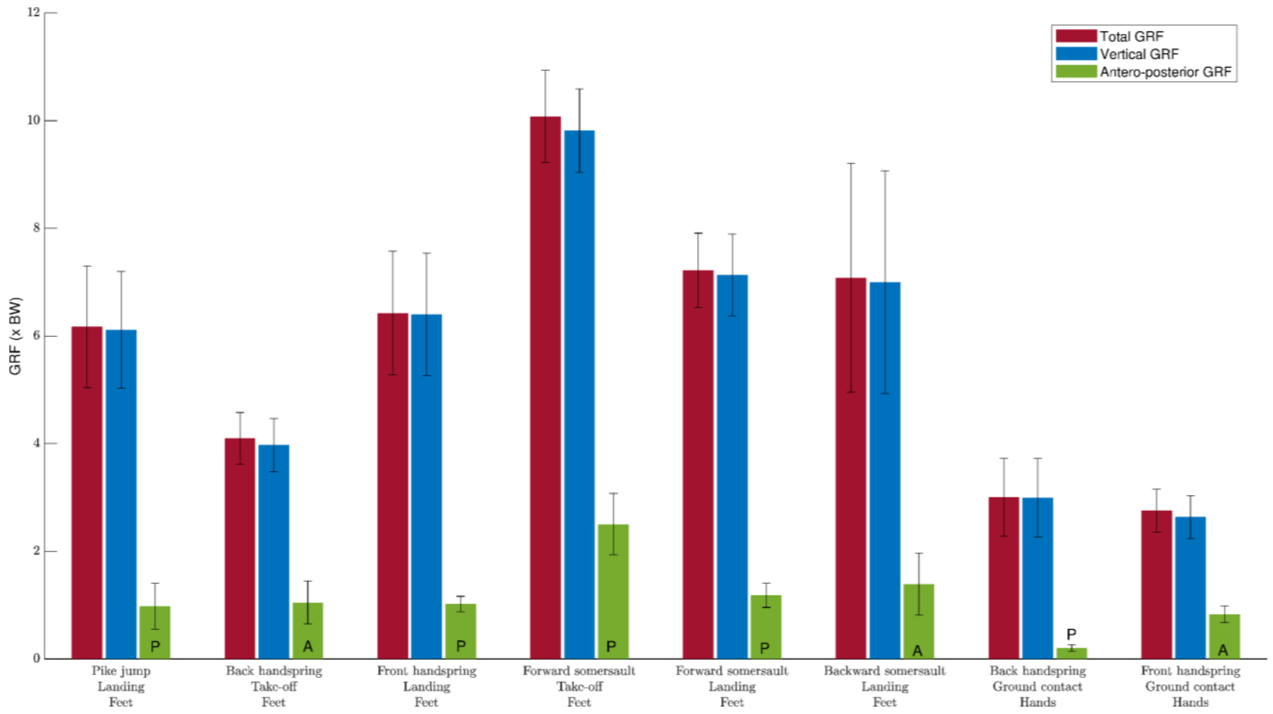

Figure 6. Averages and standard deviations of peak total, vertical and antero-posterior GRFs – P (respectively A) means the antero-posterior GRF was mostly in the posterior (respectively anterior) direction.

Lumbar lordosis at peak ground reaction forces

Figure 7 shows peak GRFs along with lumbar flexion and extension angles at the instances of peak GRFs. At landing and take-off on feet, the lumbar spine of gymnasts was in a flexed posture. At hands ground contact phase, the lumbar spine was in an extension posture for the *back handspring* in the case of MAG 1, MAG 4 and MAG 6 and for the *front handspring* in the case of MAG 4, whereas it was in a flexion posture for the others participants.

[insert Figure 7.]

Comparing the angles of flexion and extension of the lumbar spine at the instances of peak GRFs, the lumbar spine was in the most extreme flexion posture at *backward tucked somersault* landing with an average flexion of 63 ±8° (resulting from mean lumbar lordosis of 0°±16°). This maximum was followed by the lumbar flexion at *forward tucked somersault* landing and take-off and then *back handspring* take-off and *pike jump* landing with average flexion of 51 ±13°, 45 ±5°, 36 ±10° and 36 ±9°, respectively. As for the *front handspring* landing, lumbar lordosis values were close to their respective neutral values with an average flexion of 14°±6°. Regarding hands ground contact phases, for the *back handspring* three participants showed a lumbar extension of 28°±7° on average whereas the other two showed a lumbar flexion of 10°±5° on average (resulting from mean lumbar lordosis of 75°±19° overall). Finally, for the *front handspring*, all gymnasts excepted MAG 4 exhibited a lumbar flexion of 19°±13° (resulting from mean lumbar lordosis of 48°±13° overall), and MAG 4 exhibited a lumbar lordosis value close to its neutral value (slight extension of 4°).

Regarding statistics, the lumbar flexion at *pike jump* landing was significantly greater than during both the lumbar flexion at *front handspring* landing and at hands ground contact phase (p=0.03 in both cases). All p-values and associated effect sizes are reported in supplementary materials (Table S7).

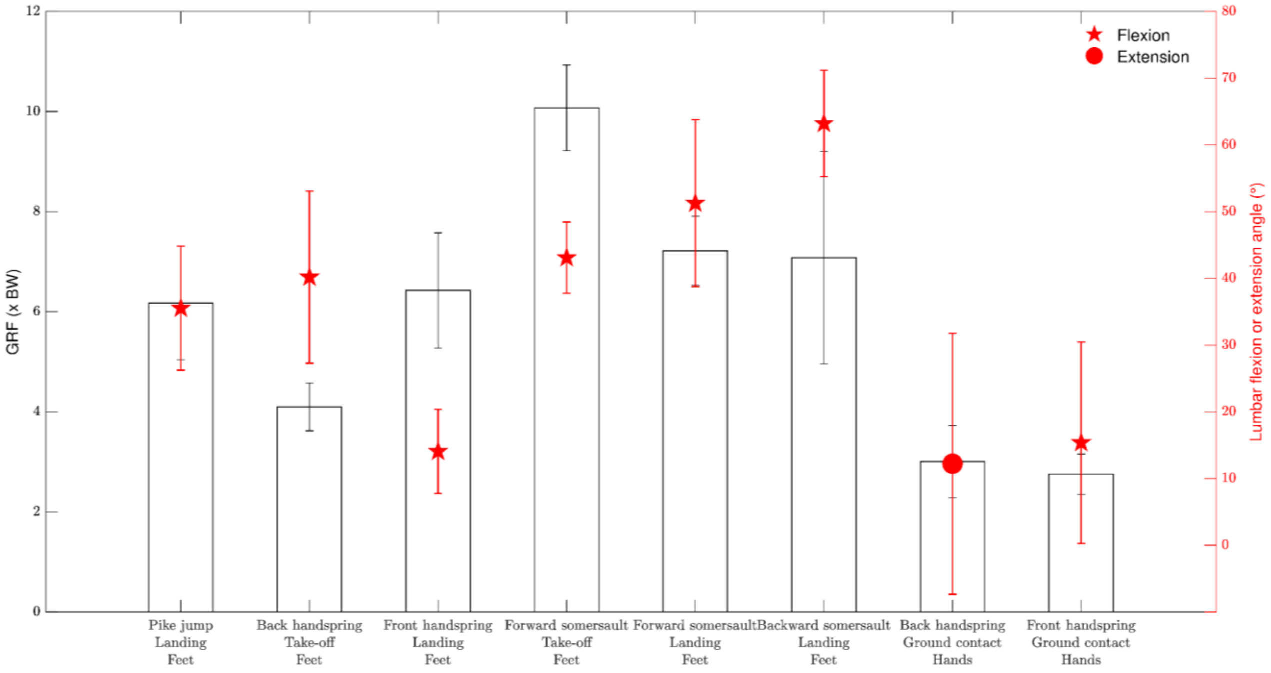

Figure 7. Averages and standard deviations of peak total GRFs (left axis) at impacts and lumbar flexion and extension angles with reference to the neutral position at the instances of peak GRFs (right axis).

Discussion and implications

The aim of the current study was to compare lumbar lordosis and peak GRFs during five typical MAG movements, as well as the lumbar lordosis at the instances of peak GRFs in order to identify the movements that pose the highest risk of lumbar spine injury.

Lumbar lordosis

During all investigated movements, certain strategies of lumbar spine FE were common to the different movements, such as the take-off, that was associated with a movement of flexion followed by an extension of the lumbar spine. As for the landing, in the case of movements requiring lumbar spine hyperextension (*round off back handspring*, *front handspring* and *backward tucked somersault*), gymnasts flexed their lumbar spine during the descending phase of the movement to support the ground impact. Throughout the *pike jump* and *forward tucked somersault* the lumbar spine of gymnasts was in a flexed posture, and landings of these two movements occurred while gymnasts straightened. In the case of these two movements, gymnasts consequently flexed their lumbar spine at the time of impact. *Round off back handspring* and *front handspring* required lumbar hyperextension postures that are more likely to cause injury than lumbar flexion postures (Pimentel et al., 2020; Watkins, 2002). In addition, the *round off back handspring* mobilised the lumbar spine from extreme flexion to extreme extension, and vice-versa, which is also known to place considerable stress on the spine (Desai et al., 2019).

Ground reaction forces

Identification of MAG movements with the highest GRFs

Peak vertical GRFs in artistic gymnastics, particularly at landings, have already been studied and results of the present study were found to be consistent (reaching 9.8±0.8 ×BW) with previous reported results. Indeed, Hall (Hall, 1986) found average vertical GRF of 6.0±0.6 ×BW at *front handspring* landing with WAG. In another study, Wade et al (Wade et al., 2012) reported peak vertical GRFs during *drop* landing (6.7±1.3 ×BW), *backsault* landing (10.3±1.7 ×BW) and *plyometric frontsault* landing (9.3±1.7 ×BW) with WAG. Because the high forces involved would result in particularly high stress across joints, ground impacts are associated with particularly high risk of injury (Desai et al., 2019; Hall, 1986; Wade et al., 2012).

In the present study, the maximum GRF was experienced for *forward tucked somersault* take-off that followed a run-up, in line with the objective of the take-off, i.e. generate maximum velocity (Nyman, 2019). Smaller GRFs found at landings were in accordance with the objective of landing, i.e. to absorb the high forces resulting from ground impact (Nyman, 2019). However, the *back handspring* take-off showed smaller peak GRF than all landings, quite logically, as gymnasts used the velocity gained during the *round off* to generate the necessary vertical velocity for the *back handspring*. The smallest GRFs concerned the hands ground contact phases, where peak GRFs were still as high as 3.0 ±0.7 ×BW and were distributed over the wrists, which are joints of smaller area when compared to the lower limbs joints, which would induce significant stress (Desai et al., 2019). All above considerations are still valid when considering only the vertical component of GRF as it represents between 94% and 98% of peak GRFs. Antero-posterior GRFs were in the order 1 ×BW and reached up to 2.5 ×BW during *forward tucked somersault* take-off. Yet such tangential forces can lead to shear forces within IVDs, that should not be underestimated with regard to the risk of injury (Tavakoli & Costi, 2018).

Identification of lumbar spine postures at risk of injury during ground impacts

The degrees of lumbar flexion and extension were analysed at the time of peak GRFs. Wade et al (Wade et al., 2012) have undertaken a similar work with WAG and showed that gymnasts flexed their lumbar spine before ground contact and continued throughout GRF absorption. In the same study, authors highlighted that at extreme lumbar flexion, back muscles are less activated and consequently the large loads experienced during impacts are even more likely to induce stress in the lumbar spine. However, authors seemed to agree that slight flexion of the spine along with-simultaneous flexion of hip, knees and ankles helps to accommodate landing by optimizing axial load distribution, limiting the risk of injuries (Nyman, 2019; Sonvico et al., 2019; Wade et al., 2012).

Results of the present study confirmed that the lumbar spine of gymnasts was in a flexed posture at landings. However, lumbar lordosis values were close to their respective neutral values in the case of the *front handspring* landing, largely due to the inability of the gymnasts to perform a perfect landing and some of them were consequently particularly backward. In addition, it was observed that the *backward* and *forward tucked somersault*, which exhibited the highest GRFs at landing, were also the movements with the most extreme lumbar flexion posture at landing. Considering Wade et al (Wade et al., 2012), the *tucked somersaults* resulted in particularly high lumbar stresses at landing. As for the *pike jump*, at landing, gymnasts were in a less extreme flexion posture while experiencing less GRFs and consequently this movement posed a lower risk for lumbar spine injury. During the hands ground contact phase of *back handspring*, the lumbar spine was in a hyperextension posture in the case of three participants. Similarly to extreme flexion, extreme extension is also associated with high loads, meaning that the lumbar spine experiences major stress because hyperextension shifts loads posteriorly and as a result, increases intervertebral shear forces (Hall, 1986).

Limitations

This study is not free of limitations. Firstly, the number of participants is limited and participants were all young. Hence, the transferability of the results to an older population of gymnasts should be done with caution before results are verified in an older cohort. In addition, results of statistical tests must be interpreted carefully. Indeed, certain differences were not found to be significant at the threshold 0.05 but were close to 0.05 (and still with a large effect size), and were based on a very limited number of participants. This is the case, for instance, of the *forward* and *backward tucked somersaults* that only five and four gymnasts respectively succeeded to perform in the laboratory conditions. The authors therefore invite the readers to also consider with interest the differences close to be significant ($p<0.1$) and with large effect size that were reported in supplementary material. However, even if the enrolment of a larger population would be beneficial for statistics, the results provided by this study already allowed for some trends to be highlighted so that coaches may be aware of the potential stresses on the spine induced by certain movements or particular parts of the movements.

Secondly, studied movements only represent a small portion of all possible MAG movements performed on the floor or on the apparatus. However, the ranges of the movements studied (frontward or backward, with or without run-up, existence of hands ground contact phase, etc.) allow certain conclusions to be extended to other artistic gymnastic movements.

Thirdly, the computed lumbar lordosis during the movements was reliant on a kinematic model. Hence, results inherently depend on the model accuracy. However, in this study, the model was personalised for every participant based on medical images. This process should limit the sources of model inaccuracies.

Finally, the parameters quantified in this study were assumed to reflect the risk of intervertebral stress. This choice was based on previous works (D’Hemecourt & Luke, 2012; Hall, 1986; Sonvico et al., 2019; Wade et al., 2012) but these hypothesis should be verified by further studies assessing the intervertebral forces (i.e. shear or compressive forces) during the studied movements. This could be done through deeper analyses, including inverse dynamics and static (or dynamic) optimization computations, which primarily require body segment inertial parameters and muscle parameters of the musculoskeletal model to be accurately personalised. However, these elements still remain challenging for the biomechanics community.

Practical implications

Under the assumptions formulated in the introduction that extreme lumbar spine flexion and extension postures and high GRFs increase intervertebral stresses, results presented above emphasised that: i) *round off back handspring* is the movement that poses the greatest risk of injury with regard to lumbar spine extreme flexion and extension postures*; ii) forward and backward tucked somersaults* were the movements that give rise to the highest GRFs; and iii) regarding the combination of high spinal curvatures and high level of peak GRFs, *forward and backward tucked somersaults and back handspring* posed the highest risk of injury. In the case of these latter movements, the correct activation of the erector spinae and the abdominal muscles is crucial, particularly at ground impacts in order to stabilise the spine and consequently reduce the risk of injury. This last point requires a special care from coaches during learning stages.

Overall the results of this study enable back pain prevention in gymnastics through training adaptations such as:

- The reduction of the number of repetitions of the identified movements.
- More targeted training adjustments for gymnasts identified as having musculoskeletal specificities that increase the risk of injuries or being in a vulnerable time (growth period, post-injury follow-up, *etc*).
- Changes in learning skills of the identified movements in order to reduce stress on the lumbar spine by soliciting other joints.

Conclusion

The aim of the present study was to compare the extreme values of lumbar lordosis and peak GRFs during five typical floor movements of MAG, as well as the lumbar lordosis at the instances of peak GRFs occurrence in order to identify the movements that are the most at risk of injury for the lumbar spine. The results have highlighted the movements that put the most stress on the lumbar spine because they involved either extreme flexion and/or extension or high GRFs or extreme lumbar postures at ground impacts. In view of the results and the training adaptations suggested, this study may help gymnastic coaches and medical staff to design more spine friendly trainings.

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No potential competing interest was reported by the authors.

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