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Biomechanical Analysis of Lumbar Spine Loading in Russian Bar Porters

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Russian bar, an acrobatic circus discipline involving dynamic loading on one shoulder, is associated with porters' low back pain. The aim of this study was to compare lumbar forces and moments generated on porters during typical maneuvers including saltos, candle jumps and consecutive jumps. A biomechanical model previously validated for lifting tasks was used to estimate L4-L5 intervertebral forces and moments. A Russian bar trio was recruited to participate in data collection, including motion capture and electromyographic measurement. Considering artists safety, external forces were indirectly estimated using a mechanical characterization of the bar and an actuator-based ground reaction force estimation. The model's validation involved assessing the agreement and the peak-cross correlation between EMG-recorded muscle activity and the model-predicted muscle activity. Results showed no significant differences between salto and candle jumps ($p>0.05$) for compressive force and moments but showed significant differences between the propulsion and landing phases ($p<0.05$), with the propulsion phase exerting the

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highest lumbar forces (12,571.7 ± 1,714.5 N) and frontal moments (68.9 ± 10.8 Nm). It appears that porters' technique enables low shearing stress (961.6 ± 419.5 N). Artists and coaches should be aware of the high compressive forces, emphasizing the need for caution, especially for young and unexperienced artists.

La barre russe est une discipline de cirque acrobatique. Le rôle du porteur consiste à soutenir une charge dynamique sur une épaule. Cette pratique peut engendrer des douleurs lombaires. La présente étude vise à comparer des forces et des moments appliqués sur la colonne lombaire des artistes lors de plusieurs mouvements type, notamment les saltos, les sauts droits et les sauts enchaînés. Un modèle biomécanique précédemment validé pour des activités de levage a permis d'estimer les forces et les moments entre les vertèbres L4-L5. Un trio d'artistes de barre russe a été recruté pour participer à une collecte de données intégrant la capture de mouvement et des mesures électromyographiques. En matière de sécurité des artistes, les forces externes ont été estimées indirectement grâce à une caractérisation mécanique de la barre et à une estimation des forces de réaction au sol sur la base d'actuateurs. Pour valider le modèle, il a fallu estimer la correspondance et la corrélation croisée maximum entre l'activité musculaire enregistrée par les capteurs électromyographiques et celle pronostiquée par le modèle. Les résultats ne montrent aucune différence majeure entre le salto et les sauts droits ($p > 0{,}05$) pour la force et les moments de compression. En revanche, il existe des écarts importants entre les phases de propulsion et de réception ($p < 0{,}05$). En effet, la phase de propulsion développe le plus de forces sur les lombaires (12571,7 ±1714,5 N) et le plus de moments dans le plan frontal (68,9 ± 10,8 Nm). Il apparaît que la technique des porteurs assure des forces de cisaillement réduites (961,6 ± 419,5 N). Les artistes et les équipes d'encadrement doivent avoir conscience de la sévérité des forces en jeu. Il est notamment crucial d'adapter les entraînements selon le niveau des artistes et leur forme physique.

Keywords: spine biomechanics, musculoskeletal model, circus, kinematics, kinetics, biomécanique de la colonne, modèle musculosquelettique, cirque, cinématique, cinétique

Introduction

The Russian bar, a captivating circus discipline born in the mid-20th century, showcases the synchronized performance of three artists: two porters and one flyer. In a classical Russian bar act, the porters support a flexible composite bar on their shoulders while the flyer performs acrobatic maneuvers by jumping on the bar. The flyer, akin to a trampoline athlete, executes aerial maneuvers such as candle jumps and saltos, described as straight jumps with backward or forward rotations. The porters accumulate energy by flexing their hips and lower extremity joints, and then extending them to propel the flyer during the propulsion

phase. During the flight, the porters ensure the flyer's safety by keeping the bar below the flyer's hips and feet. In the landing phase, the porters absorb the flyer's impact on the bar by flexing their hips, ankles and knees to optimize energy absorption.

One of the major concerns about the practice of Russian bar is the potential development of chronic low back pain among the porters.[1–4] This might result from high compressive forces, or asymmetrical forces on the porters' shoulders and back. Prior research has indicated that asymmetric lifting carries a higher risk of developing low back pain compared to symmetric lifting.[5–7] Circus companies are committed to addressing artists' injuries and implementing preventive measures. However, research investigating the spinal loads imposed on artists' bodies is lacking. Conducting comprehensive studies to understand the dynamic loading conditions experienced by porters is essential to defining effective prevention strategies for Russian bar artists.

Human musculoskeletal models serve as valuable tools for assessing joint forces applied to the body[8] using motion capture and by acquiring external forces.[9] These models have been used in sport activities including dance,[10] triple-jump[11] and golf.[12] Many biomechanical simulations have been created to assess the load on the lumbar spine during a variety of lifting or throwing activities.[5,13,14] However, no biomechanical model has been specifically tailored for Russian bar circus artists. The present study aims to quantify the load exerted on the lumbar spine of Russian bar porters using a musculoskeletal model. We hypothesized the following: 1) Russian bar generates asymmetric loads on the lumbar spine, 2) saltos generate higher loads on porter's lumbar spine than candle and consecutive jumps and 3) landing phases generate higher lumbar spine loads than propulsion and stationary phases. By undertaking this investigation, our goal is to enhance our understanding of the forces experienced by Russian bar porters and contribute to the development of injury prevention strategies for circus companies.

Methods

Experimental data collection

Ethics and participants

Written consent was obtained from three healthy Russian bar artists (two male porters, designated as porter 1 and 2, aged 31 and 41 years old, respectively, and a 34-year-old female flyer) following approval of the ethics committees of École nationale du cirque (CER 2122–15C), École de technologie supérieure (H20220512) and Cégep de Lanaudiere (2022-09-08-01). Mass was measured for each participant

(porter 1 = 74.4 kg, porter 2 = 81.7 kg, flyer = 57.8 kg). All were professional experienced circus artists having practiced Russian bar together for five years.

Experimental protocol

Video recordings were conducted during all activities. An eighteen-camera motion analysis system (OptiTrack, Natural Point, Oregon, US) tracked the movements of the porters, the position of the flyer and the deflection of the bar in 3D space. Ninety-two reflective markers were placed on one porter's body (including twelve rigid marker sets called rigid bodies) following the instructions of Beaucage-Gauvreau,[9] while eighteen markers were attached along the length of the Russian bar (Figure 1b). As noted in Figure 1a, due to limited camera availability, only one porter could be recorded at a time. Additionally, six markers were placed on the flyer's hips and ankles to follow the flyer's height and position. Eight electromyographic (EMG) sensors (Delsys Inc., Massachusetts, US) were used to record muscle activity on specific muscles: rectus abdominis (RA), external oblique (EO), thoracic erector spinae (TES) and lumbar erector spinae (LES).

Experimental data were collected for three distinct jump activities performed by the flyer:

1. candle jump: a straight jump (Figure 1c);
2. salto jump: a rotation in the sagittal plane (Figure 1d);
3. consecutive jumps: a series of successive candle jumps.

Figure 2 illustrates typical phases of these three activities according to the bar deflection. The graphs are derived from the deflection measurement taken during the data collection. All activities start with an oscillation phase characterized by small-amplitude up and down motions where the flyer's feet remain in contact with the bar. Once sufficient speed and balance are reached, the flyer initiates the jump from the bar during the propulsion phase. Subsequently, the flyer lands on the bar during the landing phase. It's important to note that a salto jump is always preceded by a single candle jump (Figure 1d), and that consecutive jumps consist of successive candle jumps of consistent heights. These consecutive candle jumps form a so-called stationary phase, where there is not a proper propulsion phase as the height of the flyer is gradually increased using the bar's flexibility almost exclusively. The landing phase is identical to that of a candle jump and, therefore, will not be analyzed in this study.

Two force plates (Bertec portable model 6090–06, Bertec Corporation, Ohio, US) measured the ground reaction forces (GRFs) generated by each of the

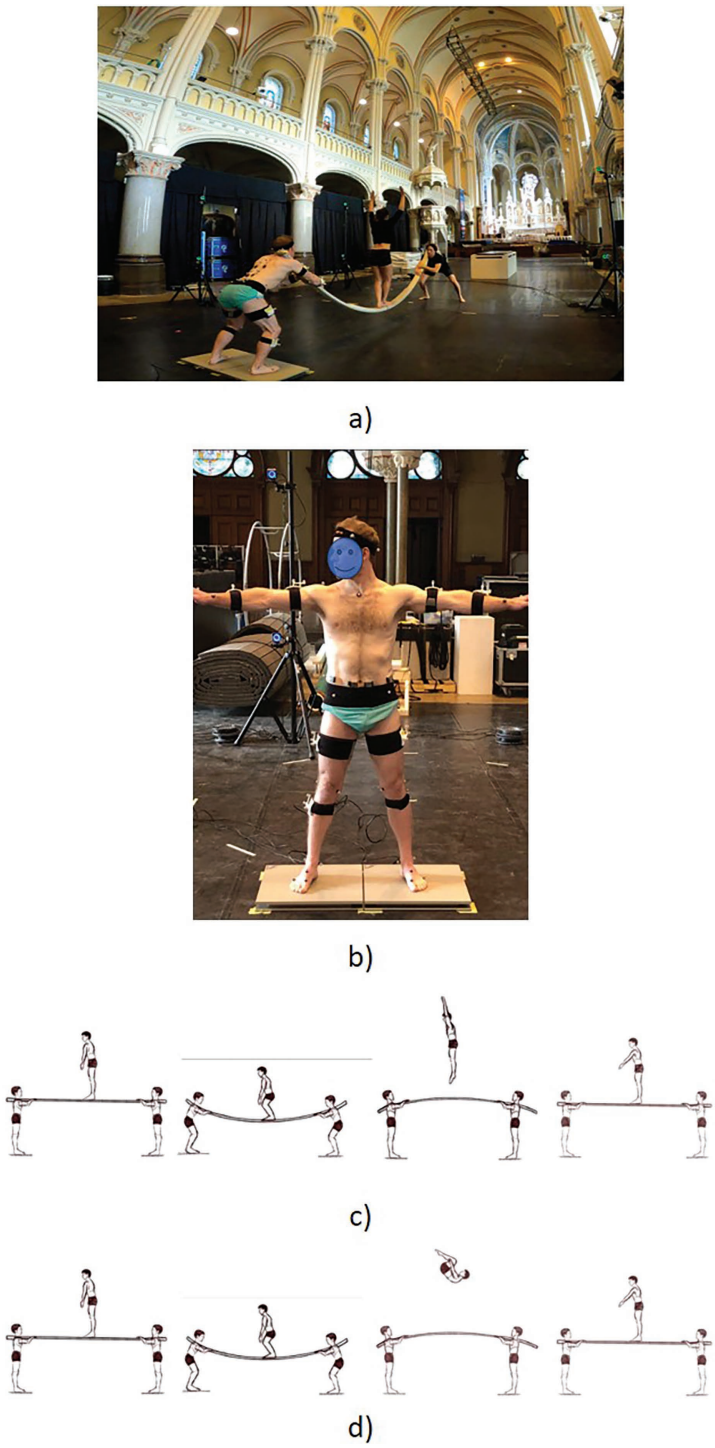


Figure 1. a) Experimental setup with the Russian bar trio. b) Porter equipped with markers and rigid bodies on the head, arms, forearms, thighs and shins. c) Illustration of a candle jump. d) Illustration of a salto jump.

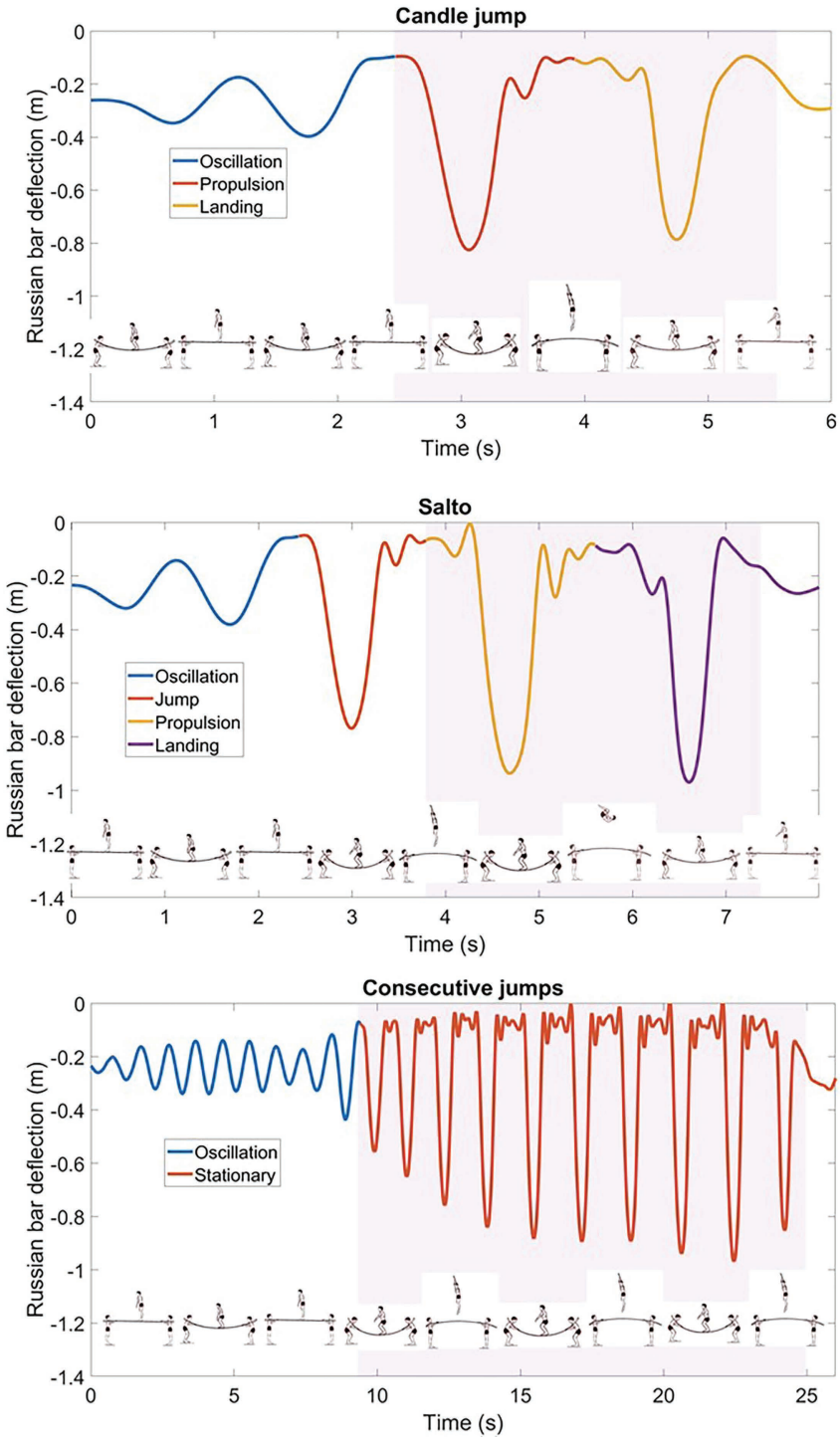


Figure 2. Bar deflection over time for three jump activities: a) candle jump, b) salto jump and c) consecutive jumps. Pictograms visually depict the activity at various phases and time points, with shaded areas representing the phases analysed in this study.

porter's feet during candle jumps lower than two meters in height. The force plates were removed for larger jumps as the porters constantly adjust their position to ensure the flyer's safety. The force plate data were ultimately used for model validation.

Methods for determination of shoulder forces

Due to challenges in directly measuring external forces on the porters' shoulders, a two-step indirect approach was employed. The first step involved characterizing the bar mechanical behavior under a static load (Figure 3a), while the second step examined the influence of dynamic loading on its mechanical response (Figure 3b).

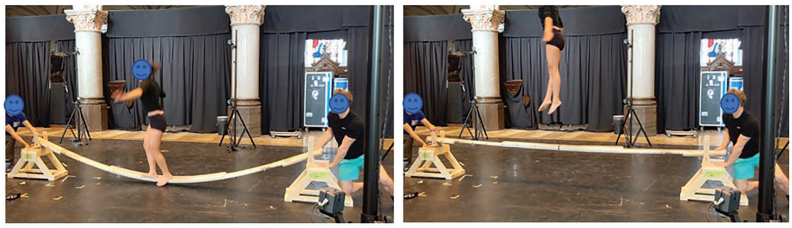
A linear relationship between static bar deflection and shoulder force was observed (Figure 4c), leading to $F = K\partial + C$ where F (N) denotes the shoulder force, K (N/m) denotes the bending stiffness of the bar, ∂ (m) represents the bar deflection and C (N) is a constant representing the mathematical error of the linear regression. (This value is negligible, as it is below 2% of the maximum force in each trial.) Using this experimental protocol, a bending stiffness of 1,703.3 N/m was determined (Figure 3c).

Jump activities can also be accurately described by observing the force applied to the porter's shoulder, as depicted in Figure 4. Jump phases (i.e., propulsion, landing and stationary phases) were further divided into loading and unloading steps. Between unloading and loading steps, the porters are in a standby phase.

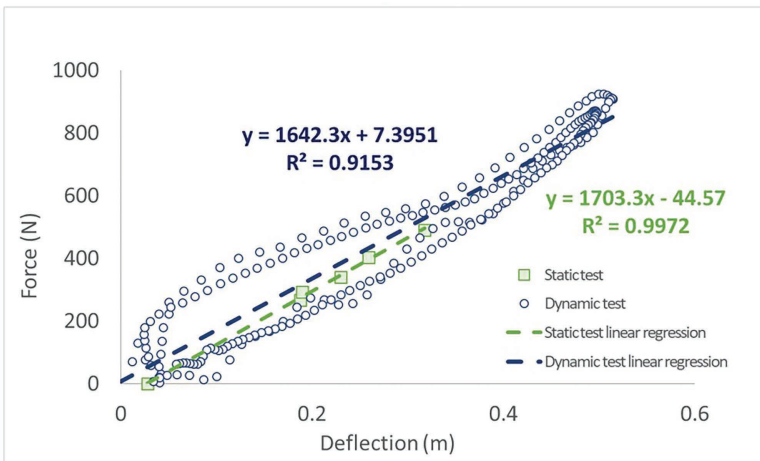
Musculoskeletal modeling

OpenSim (version 4.4)[15] was used to assess the lumbar spine loading of the Russian bar porters. OpenSim provides sophisticated computational resources and is the most-used open source platform in the biomechanics field. Accordingly, it was selected for the current research study. The full-body model of the porter is an adapted version of a comprehensive lifting model originally developed and validated for analyzing spinal loads during lifting tasks.[13] The modifications made to the original model from Beaucage-Gauvreau are presented in the Appendix. The use of a full-body model was mandatory for our study as the porters interact with external objects and use a wide range of motion. This model was validated for lifting tasks involving forward bending and is simpler than other full-body models, thus reducing computational time. The trunk exhibits three degrees-of-freedom: flexion/extension, lateral bending and axial rotation. The trunk's musculature is represented by eight major muscle groups: erector

a)



b)



c)

Figure 3. a) Experimental setup for estimating the static force applied on the porters' shoulder as a function of bar deflection. b) Experimental setup and sequence for estimating the dynamic force applied on the porters' shoulder as a function of bar deflection. c) Graphic depicting the linear relation between the shoulder's force and bar deflection in both static and dynamic conditions. This graphic also illustrates that the bar exhibits slight flexion without any applied force due to the weight of the bar and loss of structural integrity from use over time (0.03 m deflection without any force applied).

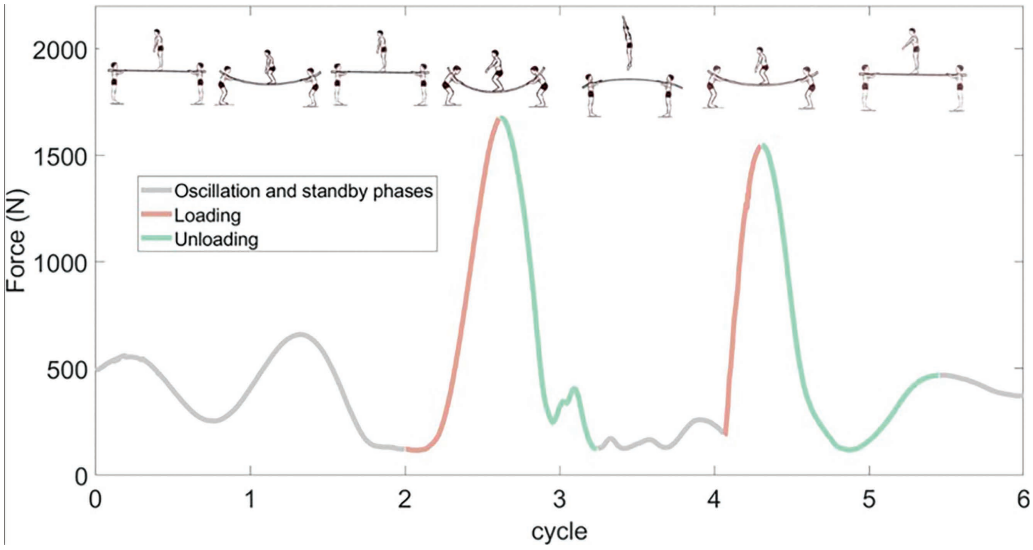


Figure 4. Shoulder force during a typical candle jump activity showing loading (red line) and unloading steps (green line) for a propulsion and a landing phase.

spinae (ES), rectus abdominis (RA), external obliques (EO), internal obliques (IO), multifidus (MF), quadratus lumborum (QL), psoas major (PS) and latissimus dorsi (LD). In a normal anatomical position, the angle convention is zero degrees and increases with joint flexion.

External forces

Three external forces were applied to the model: the force exerted by the bar on the shoulder and the two ground reaction forces. Shoulder forces were applied to the torso on a point located fifteen centimeters medial to the right acromion in the frontal plane. To ensure consistency and simplicity, the force was applied in the sagittal plane, perpendicular to the bar. The direction was obtained by calculating the normal vector of the bar at the location of the shoulder (Figure 5a and 5b). Focusing on the sagittal plane captured primary biomechanical effects while minimizing complexity. Force intensity was computed using the bar deflexion measured during jump activities and the stiffness coefficient of 1,703.3 N/m.

Computation of ground reaction forces with the model was accomplished through the implementation of inverse dynamics-based simulations using an actuator method, as described in previous studies.[16,17] This computational approach enabled the accurate estimation and quantification of the forces exerted on the ground during Russian bar, providing valuable insights into the

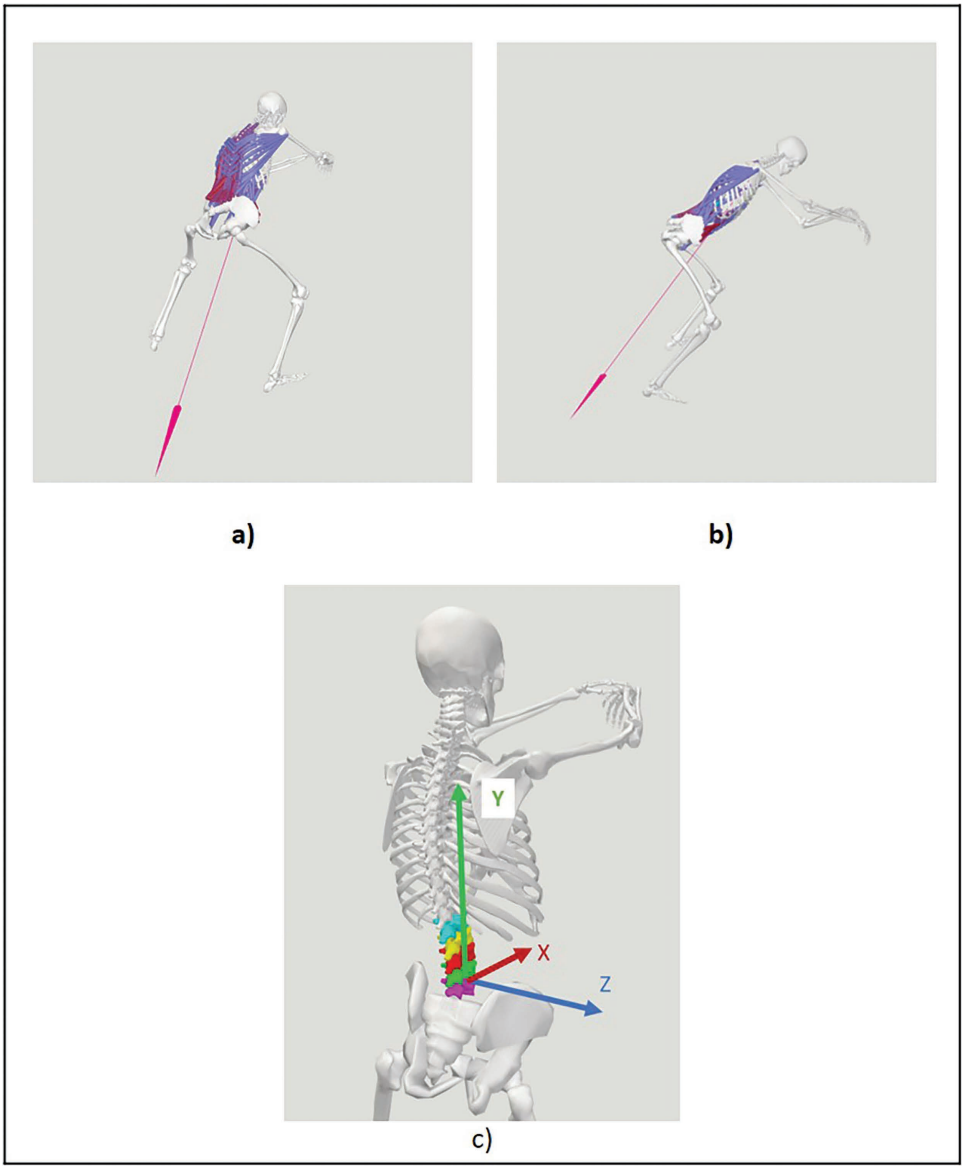


Figure 5. a) Isometric and b) lateral views of the model during a loading phase. The pink arrow represents the load applied by the bar on the right shoulder of the porter. c) Lumbar column of the musculoskeletal model (L1 in blue, L2 in yellow, L3 in red, L4 in green and L5 in purple) and the L4 local axis system.

interaction between the performers and their surrounding environment. This indirect method of estimating GRFs was validated using measurements acquired from the two force plates during a static pose and candle jumps of less than two meters in height.

Data processing

Data processing was done with MATLAB (2022a) and OpenSim. Statistical analysis was performed using Minitab (21.1). Kinematic and kinetic data were low-pass filtered using a fourth-order, zero-lag Butterworth filter with a cut-off frequency 6 Hz. EMG signals were band-pass filtered (10–400 Hz), rectified and filtered at 5 Hz, normalized to the peak activation (measured during performed maximal isometric contractions) and then normalized to the peak activation of each trial. Muscular activation of the model was filtered and normalized to maximum peak activation.

Normality of data was assessed using the Shapiro-Wilk test and showed a non-normal distribution. Statistical analysis was performed using non-parametric paired and unpaired Kruskal-Wallis tests for comparing L4-L5 joint reaction forces obtained from the different jump activities (candle, salto and consecutive jumps) and jump phases (propulsion, landing and stationary phases). Statistical tests were conducted with 0.05 significance value. L4-L5 was selected for the analysis due to its recognized role in low back pain and for comparison with existing literature.[18]

Results

Overall, 47 jumps including seven saltos, eleven candle jumps and 29 consecutive jumps were recorded. Propulsion and reception phases were extracted from all recordings of candle jumps and saltos (EMG, kinematics and joint reaction forces), while stationary phases were extracted from consecutive jumps. For the kinematic analysis, propulsion and reception phases were further subdivided into loading and unloading steps. Compressive force is the force along the Y-axis expressed in local body frame. The shearing force is defined as the Euclidean norm of the shear force along the X-axis and the shear force along the Z-axis.

Jump analysis

Kinematic analysis

The propulsion and landing phases displayed distinctive articular kinematic patterns, as illustrated in Figure 6, indicating that both porters used different strategies for propelling and receiving the flyer. During the propulsion phases, the porters exhibited hip flexion during the loading step and hip extension during the unloading step. Conversely, in the landing phases, hip flexion steadily increased

throughout the cycle. Propulsion phases showed left and right hip flexions angles of 81.4° ± 4.2° and 75.2° ± 14.3°, respectively. Stationary phases mirrored propulsion phases though with reduced motion at the left (43.0° ± 18.9°) and right (40.9° ± 16.1°) hips. This suggests that the porter predominantly leveraged the bar's flexibility for upward propulsion during consecutive jumps. In the landing phase, the range of hip flexion was slightly higher than in the propulsion phase (left: 93.3° ± 4.9°; right: 91.1° ± 4.9°). Small changes in lumbar lordosis angle were recorded (<10°) as the porters kept the lumbar column "straight".

Joint reaction forces

Table 1 presents joint reaction forces at L4-L5, expressed in the local coordinate system of the L4 vertebra (Figure 5). No significant differences were found in compressive forces between candle and salto jumps during propulsion ($p=0.143$) or landing ($p=0.364$) phases. However, paired Kruskal-Wallis test applied to both candle jumps and saltos indicate that the propulsion phases generated significantly higher forces than the landing phase ($p<0.001$). Additionally, the stationary phases exhibited significantly lower forces than the propulsion ($p<0.001$) and landing phases ($p=0.038$).

Salto jumps during propulsion induced significantly higher lumbar shear forces than candle jumps ($p=0.04$). Salto jumps showed higher forces during the propulsion than the reception phases ($p=0.004$). A paired test showed that there were no significant differences in shear forces between the propulsion and landing phases ($p=0.163$). Shear forces for both propulsion and landing phases were significantly lower during stationary jumps than in candle jumps ($p<0.015$).

Across all phases, the bending moment (Mz) in the sagittal plane exhibited the highest magnitude, closely followed by the moment in the frontal plane (Mx). The moment Mz was significantly higher in the propulsion phases than in other phases ($p=0.029$ vs landing, $p<0.001$ vs stationary). The moment in the frontal plane Mx was significantly higher in the propulsion phases than in other phases ($p=0.002$ vs landing, $p=0.014$ vs stationary). Mx was also significantly higher during the propulsion phases of salto jumps than during the propulsion phases of candle jumps ($p=0.04$). No other significant differences were found for Mx and Mz.

Discussion

This study utilized a complete musculoskeletal human model to estimate the load applied on the lumbar spine of Russian bar porters. As anticipated, the largest moments were exhibited in the sagittal plane (bending moments Mz)

Table 1. Mean value of the peak internal forces and moments in the L4-L5 joint and hip flexion across all jump phases.

Jump	Phase	Hip flexion max (deg)	Joint reaction forces		Joint reaction moments		
			Compression (N)	Shear (N)	Mx (Nm)	My (Nm)	Mz (Nm)
Candle (11 jumps)	Propulsion	90.8	10,775.1	654.5	75.9	38.7	76.8
	SD	*8.7*	*2,530.9*	*275.2*	*38.9*	*22.4*	*26.3*
	Landing	90.8	7,807.4	557.9	38.1	11.5	63.3
	SD	*8.7*	*1,142.5*	*84.2*	*38.1*	*31.1*	*12.0*
Salto (7 jumps)	Propulsion	91.6	12,571.7	961.6	121.5	60.2	89.8
	SD	*7.9*	*1,714.5*	*419.5*	*55.9*	*30.0*	*29.8*
	Landing	92.7	7,309.7	696.2	40.7	7.4	69.0
	SD	*7.9*	*645.1*	*86.7*	*11.4*	*23.9*	*5.3*
Consecutive (29 jumps)	Stationary	37.5	6,353.6	434.9	22.8	2.4	42.9
	SD	*21.3*	*1,414.1*	*51.2*	*10.8*	*15.7*	*8.4*

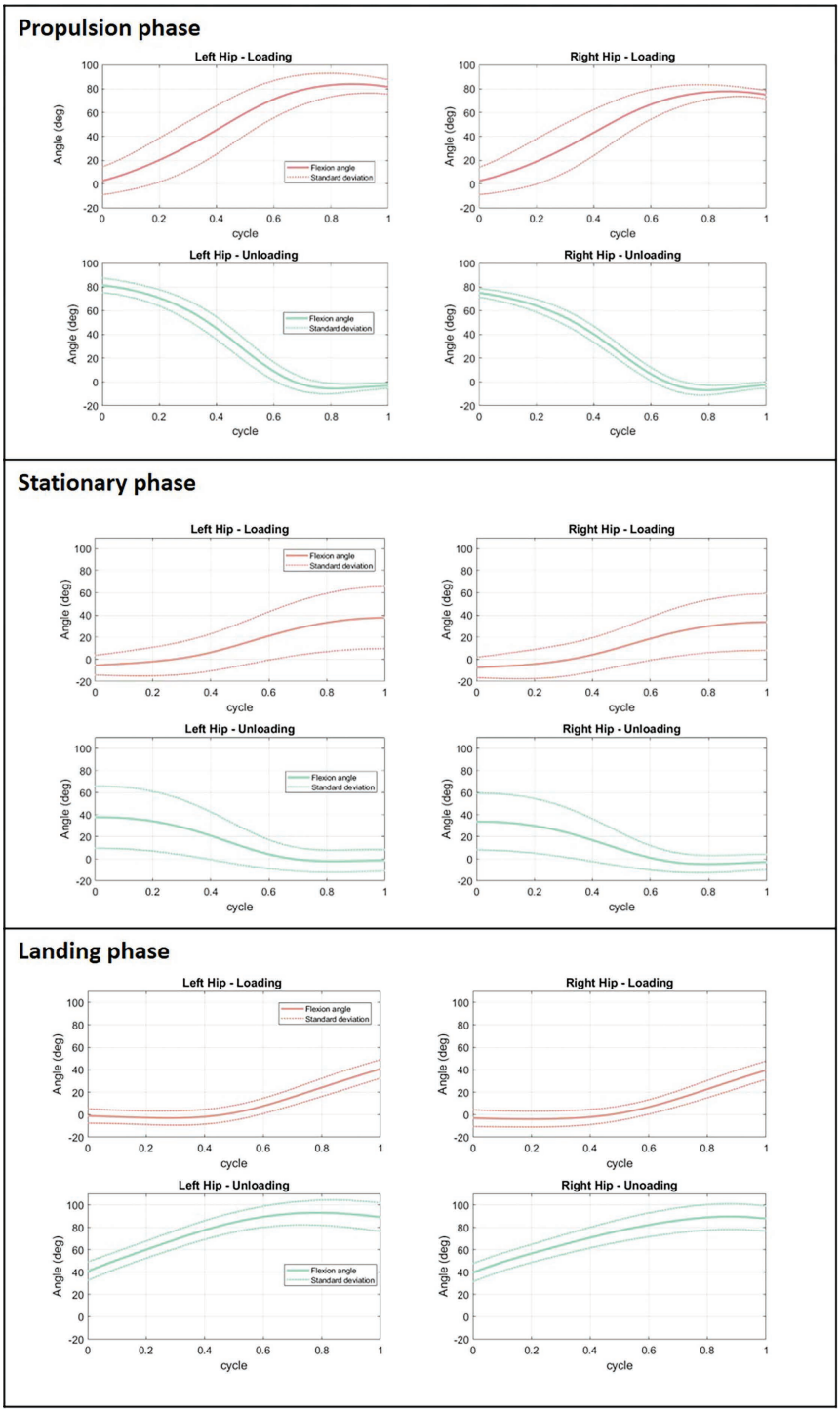


Figure 6. Hip joint angle during the three phases of jumps for the two porters: propulsion (eighteen jumps); stationary (29 jumps); landing (eighteen jumps).

for all jump activities, reflecting the need for the porter to flex their hips to control the bar's reaction. Consistent with our first hypothesis, the moment in the frontal plane (lateral bending) was similar in magnitude to the bending moment, suggesting an asymmetric load on the porter's back. Our second hypothesis was not supported. Salto jumps exhibited significantly higher compressive forces and moments than successive jumps. These jumps also showed higher shear forces than candle and successive jumps. However, there were no significant differences in lumbar compressive forces and moments between salto and candle jumps. Our third hypothesis could not be confirmed with our results, as the propulsion phase did not generate greater forces than landing phases. Ultimately, jump height and hip flexion significantly contributed to the L4-L5 compressive forces, particularly in the case of successive jumps (R^2=0.74 and 0.73, respectively).

Our findings indicate that a Russian bar porter endures high compressive lumbar forces, reaching up to 12,571 ± 1,715 N, but relatively low moments, with a maximum value of 121.5 ± 55.9 Nm. This can be explained by the observation that the porter maintains their low back in a straight position (low lumbar spine range of motion < 10°) limiting the lever arm on the vertebrae and aligning their low back with the external force applied on their shoulders in the sagittal plane. In comparison, Eltoukhy et al. validated a model for assessing weightlifting exercises, showing values of 6,224 ± 1,753 N (snatch), 7,963 ± 2,784 N (deadlift) and 8,701 ± 3,263 N (clean), with bending moments in the sagittal plane of 734 ± 331 Nm (deadlift) to 1,731 ± 1,410 Nm (clean).[19] Schmid et al. reported compressive values up to three times body weight for lifting tasks, whereas our study identified forces reaching up to ten times body weight.[20] While our calculated forces may appear remarkably high, previous studies have seldom delved into such high efforts. Comparable loading conditions were found in strongman activities,[21] where participants sustained compressive forces surpassing 12,000 N and moments exceeding 300 Nm during the super yoke walk and keg walk (with a 155 kg keg on the right shoulder), respectively.

The model effectively estimates lumbar spine loading in Russian bar exercises. However, prudence is advised when interpreting our quantitative results, given the reliance on assumptions and the constraints posed by our small sample size. Specifically, there are certain limitations in the estimation of external loads, as both of our external forces are indirectly estimated. While the bar characterization reliably estimated the vertically-applied loads in the sagittal plane, its accuracy diminished when assessing loads applied in the frontal plane. The interaction between the bar and the porter's body is intricately complex, as the bar is "blocked" between the neck and the arm/forearm. This interaction is heavily influenced by the porter's musculature and specific morphology. While applying the external force through a point near the acromion may not be the most precise

representation, the agreement between calculated and experimentally measured ground reaction forces supports this simplification. Another interesting point that is not addressed in this study is the coordination between all three artists, which might influence lumbar biomechanical responses. A new study should specifically focus on the coordination between the flyer's jump and the porters' movements.

This model will assist coaches and artists in evaluating new bar prototypes and techniques. It helps quantify mechanical stress on artists, thereby aiding in injury prevention by identifying risk factors. Furthermore, in light of our findings, artists and coaches should consider various factors. Given the direct correlation between shoulder force and the mechanical characteristics of the bar, opting for a more flexible bar is advisable. This modification would primarily alleviate shoulder loading but might limit artistic possibilities. Additionally, a bar that is too flexible could pose a risk, potentially touching the ground during landing and endangering the flyer. Consequently, an optimal range of bar flexibility values must be found. As the forces involved in this discipline are exceedingly intense, special precautions are recommended, particularly for young and novice artists. Coaches should implement suitable exercises and training programs to mitigate exposure to high forces or ensure that artists are physically prepared to withstand these forces. Repetitive force on the spinal column can potentially lead to a decline in low back function.[22] As illustrated by Kazemi,[23] joint reaction forces increase with muscular fatigue, highlighting the need to limit training duration to prevent such effects. Enhanced co-contraction has the potential to reduce intervertebral forces.[24]

Conclusion

In conclusion, the proposed model has provided valuable insights into the loads exerted on the lumbar spine of Russian bar porters, making a substantial contribution to the understanding of the lumbar spine biomechanics associated with this captivating acrobatic discipline. Future research should focus on refining the modeling of external forces and muscle actions to improve accuracy. Exploring various loading scenarios, including more acrobatic maneuvers at different heights, would be intriguing and could further enhance our comprehension of the discipline while supporting the well-being of circus artists.

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Appendix

Inverse kinematic (IK), inverse dynamic (ID), static optimization (SO) and joint reaction analysis (JRA)

Inverse kinematic (IK) was conducted using the OpenSim graphical user interface. Inverse dynamic (ID), static optimization (SO) and joint reaction analysis (JRA) were carried out using available MATLAB scripts provided by OpenSim. MATLAB scripts enabled the results analysis and graph generation.

Bar characterization

A dedicated experimental test bench comprising two rigid supports with a three-axis load cell (Mini85, ATI industrial automation, Michigan, US) screwed onto one of the supports was built (Figure 3a). The Russian bar was positioned on top of the rigid supports and the load cell. Loads of 40, 80, 120, 160 and 200 kg were successively applied at the middle of the Russian bar using straps and gym weights while the OptiTrak motion capture system (previously described) was used to track the position of the eighteen optical markers placed on the bar. This setup allowed for the measurement of the force acting on the support as a function of the bar deflection. The force at the porter's shoulder was estimated by calculating the component of the force perpendicular to the bar's shape.

In a second step, a dynamic test showed no significative impact of loading speed on structural deformation occurring during a static loading. Consequently, by monitoring bar deflection during jump activities using the eighteen optical markers, it was possible to calculate the force exerted on the porter's shoulder using Equation 1.

Model modification and validation

One major modification regarding maximal isometric force helped to estimate spinal loads for Russian bar porters. It was observed that the model's overall strength was inadequate for the intended purpose, as some calculations did not converge during the initial round of testing. Subsequent tests indicated that increasing the maximum isometric force enhanced the convergence of the calculations. Factors of two, three, five and ten were evaluated. According to our tests, the results did not vary significantly across the different factors applied.

Consequently, a conservative factor of ten was applied to all maximum isometric forces in the model.

The model was validated using two different methods: a method using muscular activity comparison and a method using GRF comparison. In the first method, muscle activity recorded via EMG was compared phase-by-phase, across all jumps, to model-predicted muscle activations. Each muscle activity recorded with EMG was normalized to its peak maximal voluntary contraction (MVC), while the model's muscle activation was the sum of the muscle fascicle activations normalized to their peak activation across each jump activity. The EMG validation relied on two criteria: the peak cross-correlation between the two signals signal using Matlab *xcorr* function[13] and the agreement criteria proposed by Actis et al.[25] The agreement criteria involved calculating the duration expressed as a percentage of each jump cycle when both EMG and muscle activity predicted by the model are either above or below a threshold of 0.5.[25] The combined use of these criteria greatly enhanced the model's validation credibility.

In the second method, ground reaction forces computed by the actuator-based method were directly compared to the force platform acquisitions during the propulsion and landing phases of candle jumps of less than two meters in height. Validation was assessed using two criteria: the root mean square error (RMSE) and the peak cross-correlation between the GRF total forces.

EMG validation

Figure 7 and Figure 8 display the normalized muscular activation values of eight muscle groups from the model estimations and experimental measurements for the propulsion, reception and stationary phases, averaged across all jump activities. Peak cross-correlation values ranged between 0.64 and 0.89, and agreement values ranged between 52% and 86% (Table 2).

The correlations between EMG and OpenSim muscular activation were predominantly high for most muscle groups, with the lowest peak cross-correlation at 0.64 and the highest reaching 0.86. In the original model validation by Beaucage-Gauvreau, peak cross-correlations were reported up to 0.93, and values above 0.82 were observed for all back muscle groups.[13] The agreement values, falling within the range of 52 and 89%, were deemed acceptable. As emphasized by Actis et al.,[25] agreement can be influenced by normalization and processing methods. Furthermore, the use of EMG sensors presented challenges due to noise generated by the impact of the Russian bar and the physical strain on the porters. This resulted in some sensors being displaced during the trials and noisy signal. In a broader context, our findings seem to be low compared to studies specifically dedicated to validating lumbar models,[25–27] underscoring

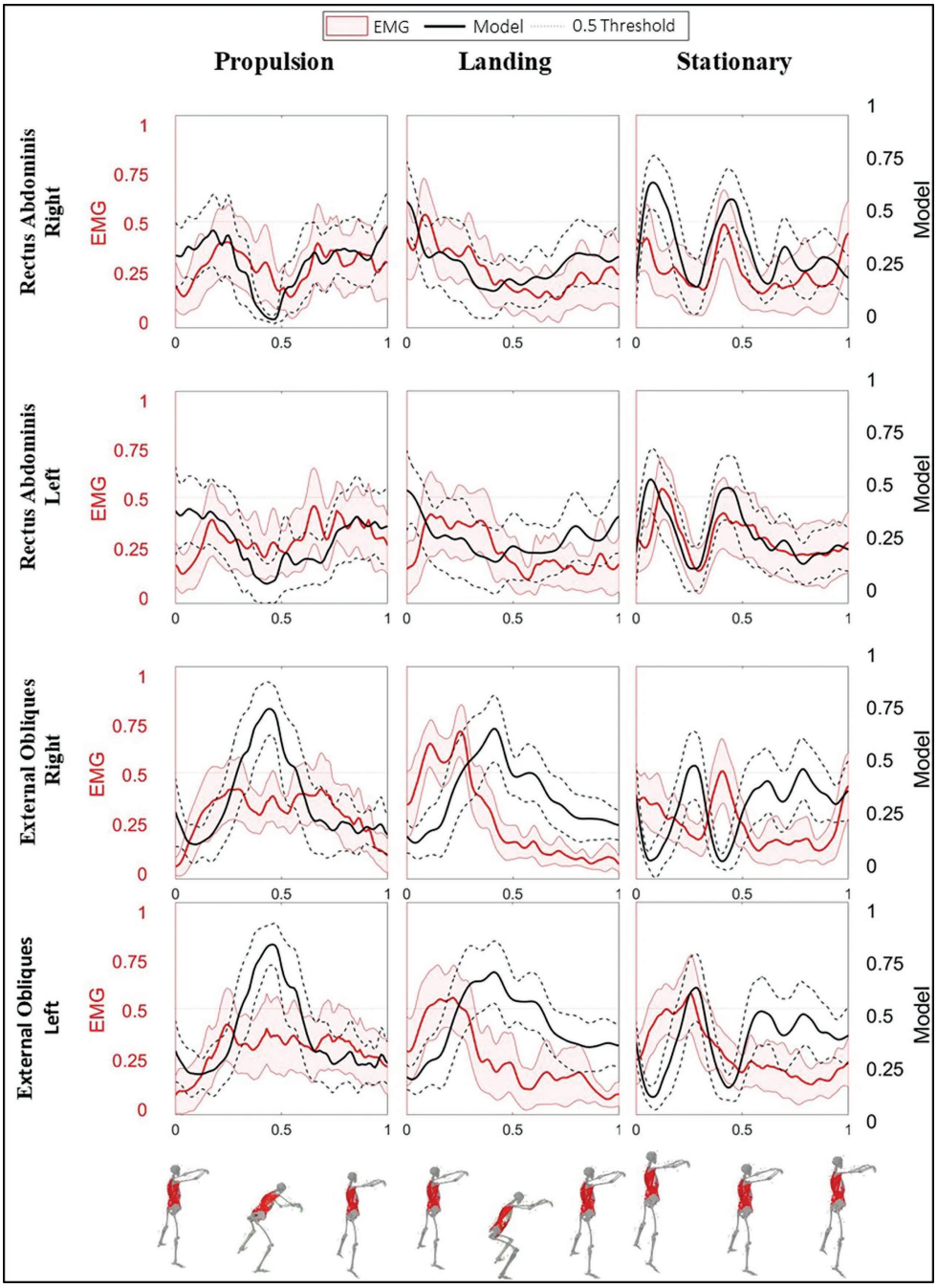

Figure 7. Mean muscular activation values recorded by EMG sensors (red) and estimated by the model (black) for four muscles groups: right rectus abdominis (RRA), left rectus abdominis (LRA), right external obliques (REO) and left external obliques (LEO). The dashed lines represent one half standard deviation from model values. The horizontal dotted lines represent the one-half threshold value for agreement calculation.

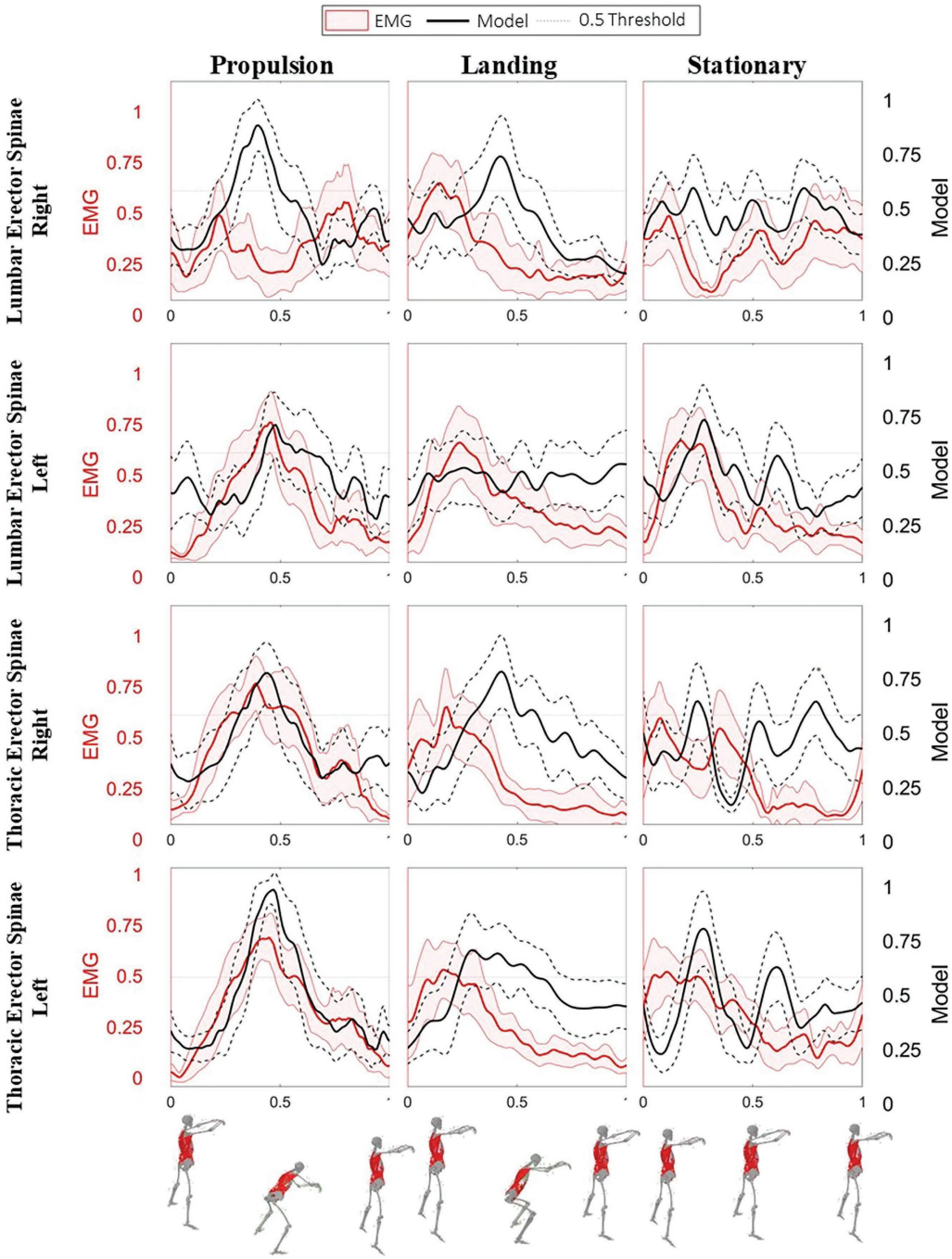

Figure 8. Mean muscular activation recorded by EMG sensors (red) and estimated by the model (black) for four muscles groups: right lumbar erector Spinae (RLES), left lumbar erector spinae (LLES), right thoracic erector spinae (RTES) and left thoracic erector spinae (LTES). The dashed lines represent one half standard deviation from model values. The horizontal dotted lines represent the one-half threshold value for agreement calculation.

Table 2. Average peak cross-correlation and agreement values between muscle activation from model estimations and experimental measurements across all jump activities.

Jump	Validation	Propulsion	Landing	Stationary
Rectus Abdominis Right	Correlation	0.73	0.77	0.74
	Agreement	68%	67%	63%
Rectus Abdominis Left	Correlation	0.76	0.68	0.77
	Agreement	64%	66%	64%
External Obliques Right	Correlation	0.82	0.83	0.83
	Agreement	54%	59%	61%
External Obliques Left	Correlation	0.75	0.77	0.81
	Agreement	59%	55%	63%
Lumbar Erector Spinae Right	Correlation	0.70	0.67	0.66
	Agreement	58%	66%	63%
Lumbar Erector Spinae Left	Correlation	0.77	0.75	0.78
	Agreement	72%	70%	71%
Thoracic Erector Spinae Right	Correlation	0.78	0.72	0.70
	Agreement	64%	62%	61%
Thoracic Erector Spinae Left	Correlation	0.89	0.85	0.64
	Agreement	75%	52%	86%

the need for an enhanced model meticulously tailored for circus artists given the highly specific demands of their activities.

GRF validation

Figure 9 illustrates the comparison between the estimated GRFs and the forces measured experimentally for both propulsion and landing phases of candle jumps (less than two meters in height). The RMSE for the propulsion phase was 191 N, with a mean difference of 13.6%. In the landing phases, there were more discrepancies, with an RMSE of 245 N and a mean difference of 19.9%. Despite differences between measured and estimated values, most results fall within one standard deviation, as supported by a cross-correlation of 0.99. Figure 10 shows

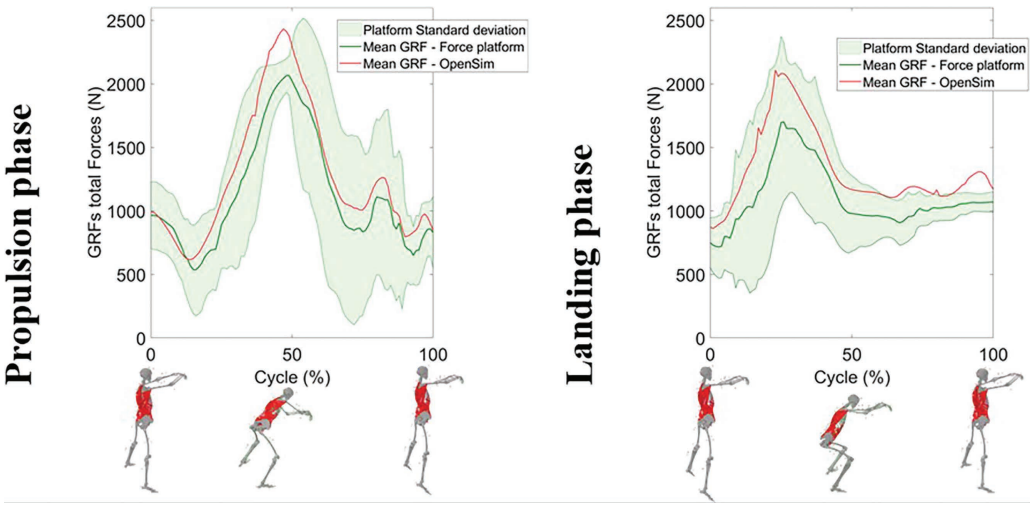

Figure 9. Comparison between estimated GRFs (red lines) and GRFs measured experimentally (green lines) on both force plates during propulsion and landing phases (two porters and eighteen jumps).

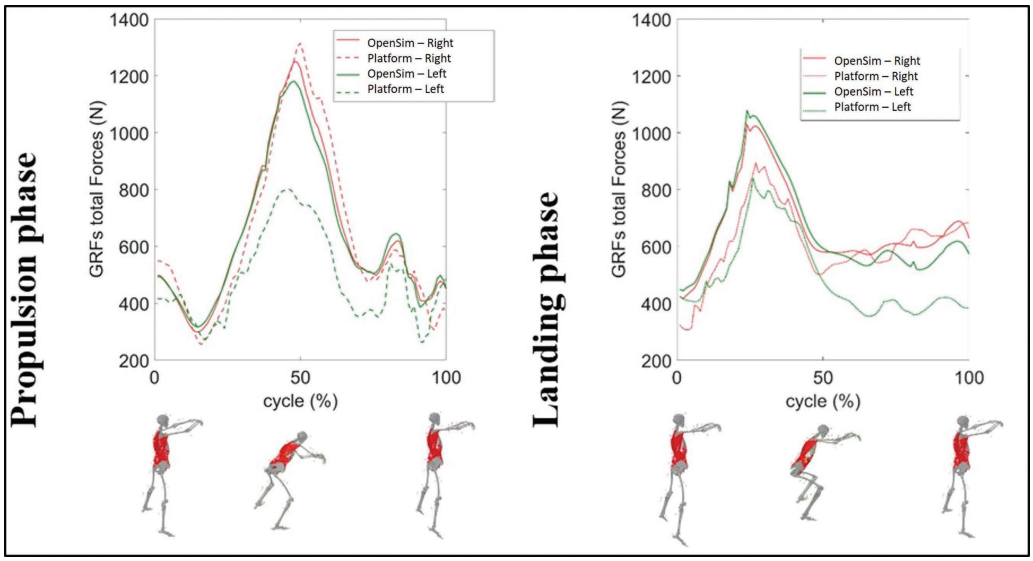

Figure 10. Comparison between estimated GRF (solid lines) and measured GRF (dashed lines) for the right foot (red lines) and left foot (green lines) during propulsion and landing phases.

that differences in the propulsion phases could be associated with a poor distribution of forces between feet from the actuator-based method. For the landing phases, there were fewer differences measured between feet, and the model seems to overestimate forces for both feet.