Repeatability of force signals in aerial circus straps

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Abstract

The aim of the present study is to develop a method for assessing movement variability of circus acrobats. An analysis of the repeatability of force signals is used to quantify variability. Six students from the National Circus School of Montréal performed 5 to 10 trials of an acrobatic movement called dislock in aerial circus straps while tension force was measured at the hanging point of the aerial apparatus. The repeatability of force signals was calculated with three statistical methods, the time-averaged standard deviation (STD), the intraclass correlation (ICC) and the root mean square error (RMSE), and compared with the ratings of a circus coach who ranked each acrobat with regards to the movement variability. The STD and the ICC methods are commonly used to quantify the agreement between measurements in biomechanics, while the RMSE method is regularly employed to quantify the agreement between measurements and a model. It is found that all participants performed the movement with little variability ($ICC \geq 0.8$). The results of the three methods were in good agreement with the assessment of the coach. The RMSE method, in particular, showed perfect agreement and is therefore considered better. In the future, the proposed method could be used by coaches or by artists repeating alone and thus providing a new form of feedback.

Keywords

Movement variability, repeatability of force signals aerial circus straps

Introduction

To become skilled at circus, acrobats must learn how to coordinate their body movements with tremendous precision. As a high-level athlete, when performing the same acrobatic movement a number of times, a circus artist is expected to always use the same technique. There is no exception for acrobats performing the discipline of aerial straps, which is an apparatus made of two thin and suspended bands of cotton or nylon webbing[1]. However, variability occurs: even after years of training, elite athletes cannot reproduce perfectly identical movement patterns[2;3]. Movement variability has been studied for some time in sports including walking[4], running[5], baseball[6], basketball[7;8], athletic jumping[9] and gymnastics[10;11]. Researchers focused on analyzing the influence of skills on the movement variablity. But it is not clear that decreased variability occurs with higher level of expertise. The hypothesis is that greater mastering allows athletes to cope with environmental perturbations and it facilitates changes in coordination patterns. The study of movement variability in sports usually consists in the analysis of the repeatability of kinematic data measured from a camera motion analysis system, sometimes accompanied with force data measured from force platforms[5;6;9–11]. Repeatability refers to the variation in repeated measurements made on the same subject under identical conditions. Various statistical methods are used to report the analysis of repeated measurements.

Three statistical method were selected to quantify the repeatability of force measurement: the standard deviation (STD), the intraclass correlation (ICC) and the root mean square error (RMSE). The standard deviation of repeated measurements on the same subject is often used in the literature to assess measurement error[3;12]. Another common metric to quantify the reliability of measurements in the

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movement science literature is the intraclass correlation and is expressed as the ratio of variances[3;12]. As for the root mean square error, it is regularly employed in model evaluation studies by measuring the difference between two values[13]. It appears that the three methods selected have similarities but they do not give the same information. Based on definitions developed by Bartlett and Frost[12] and for our application, the best suited method to quantify the agreement between measurements would be the standard deviation.

Variability can be defined in statistical terms as the variance of data about the mean and is usually quantified by the size of the standard deviation[6–8]. The standard deviation is often used on one kinematic variable at a precise time. For example, Hiley et al.[11] calculated the standard deviation for the shoulder and hip angle at the instant of maximum and minimum hip and shoulder angle in high bar. The coefficient of variation, defined as the ratio of the standard deviation with respect to the mean, can also be used[8] and is a useful marker of gait instability[14]. The variability of cadence in walking can be estimated by the mean of the standard deviation from stride time series[15].

One prominent method in reliability or repeatability quantification is the intraclass correlation (ICC)[16]. The ICC coefficient represents agreement between many evaluation methods of the same group. ICC is often used to assess the repeatability of electromyographic (EMG) signals[17;18] but it can also be employed to measure the variability of biomechanical data[19;20]. ICC indicates the proportion of the global variance that can be attributed to the variability between subjects with respect to the the variability of the remaining parameters such as repeated days, trials or judges and is given by the formula:

$$ICC = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_d^2} \quad , \tag{1}$$

where σ_s^2 is the variance between subjects and σ_d^2 is the variance due to day-to-day variability (or trial-to-trial or judge-to-judge). It is current practice to accept values above 0.8 as excellent repeatability ICC, whereas values below 0.6 indicate poor repeatability[21].

The Root Mean Square Error (RMSE) (also called the root mean square deviation, RMSD) is frequently used to measure the difference between values predicted by a model and the values observed[13;22]. The

RMSE is defined as the square root of the difference between the prediction and the estimation. It may also be employed to measure the repeatability between signals. Rainoldi et al.[18] calculated the mean squared error (MSE) due to the subject's differences to find if the variability of EMG signals is due to subject variation or to noise variations. He also measured the repeatability of EMG variables by both the ICC and the MSE methods.

Other techniques have been used to quantify variability in biomechanical measurements. Sidaway et al.[23] presented the normalized root mean square (NoRMS) error, a method for measuring the variability of biomechanical data as angle trajectories. The NoRMS is well suited for the case of human movement data in which the relationship between the two variables is non-linear in a significant portion of the time interval. Given the limited amount of research done with the NoRMS technique as pointed out by Wheat and Glazier[24], the proposed study focused on more documented methods.

Although every circus artist attempts to create their own unique acrobatic movement, they want to be repeating the movement with the same technique each time. Many biomechanists have argued strongly that learning to cope with noise helps skilled athletes to succeed a technical task or movement[25]. However, human movement will always contain noise and variability for professional circus artists is an unwanted source of error that should be kept low. Professional artists must perform acrobatic movements properly and with the same timing every time in order to be synchronized with the music and with the group choreography. A circus coach will check for biomechanical anomalies influencing variability and instruct the learner on how to perform consistently under different conditions such as in front of an audience.

Many cameras would be required to set a motion capture system to have proper data. It seems impossible to install a measurement system in a circus gym in the context of training or class; the circus gym is crowded with many students performing in different disciplines. In addition, installing markers on the acrobat require significant additional time for each performance. Since it is not practical to measure kinematic parameters during circus training, a new, less invasive way to measure movement variability has to be found. The aim of the present study is to measure the variability in the dislock movement repeated many times by many artists in aerial straps. We achieve this through analysing the repeatability from non-invasive measurement, that is, the tension force signals measured at the hanging point of the aerial straps. Three methods, the mean of standard deviations, ICC and RMSE, are used to measure signal variability. The results are compared with performance and variability ratings determined by a circus coach. The goal of the comparison is to find the best method for assessing movement variability from force measurement. The influence of parameters, such as movement characteristics and artist characteristics, on the force signal is studied through variance analysis. It is hypothesized that one of the three statistical methods selected will provide a good assessment of the movement variability, which means good agreement with the rating of the circus coach would be reached.

Methods

Participants and circus equipment

Six students from the National Circus School of Montréal were recruited as participants (average age: 20.3 years, standard deviation $s = 1.2$; average mass: 66.3 kg, $s = 3.9$; 1 female and 5 males). The higher education program of the National Circus School is a 3-year program that leads to professional career. All students were injury free at the time of testing. They signed informed consent forms in line with the regulations of the ethical committee of École Polytechnique de Montréal.

Every participant in the study performed with pairs of straps provided by the National Circus School. The straps are long ribbons of aramid fibers (SA20, Circus Concept, Québec, Canada), 300 to 500 cm in length, 3.8 cm in width, and 0.2 cm in thickness. Although elastic straps also exist in the circus discipline, all participants in the study performed with "stiff" (*i.e.* low elasticity) straps.

Dislock movement

The *dislock* movement is similar to the backward longswing on rings[27–29] except that the movement is initiated and completed in pike position. The pike position is performed with the knees straight and the body bent at the waist (Figure 1 (a) & (f)). The dislock movement consists of six phases: an initial

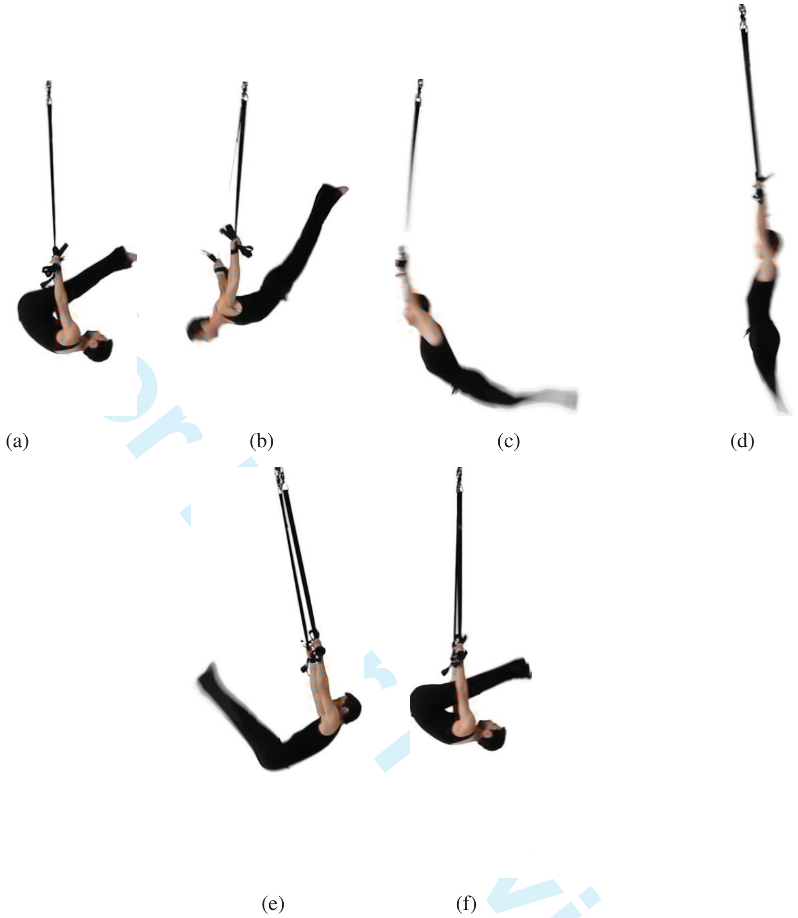


Figure 1. Sequence of an acrobat performing a dislock movement on straps. Reproduced with permission and retrieved from the The Circus Dictionary[26]

handstand phase in the pike position (a), a leg kick to extend the body (b), a descending phase (c), a swing beneath the straps (d), an ascending phase during which the acrobat takes a piked configuration (e) and the final handstand in the pike position (f). This movement is called a dislock movement because the acrobat can suffer shoulder dislocations if the shoulders are not rotated fast enough.

A typical force signal measured at the hanging point for a dislock movement is shown in Figure 2. The letters (a) to (f) refer to the sequence of images in Figure 1. At the beginning (a) and at the very end of

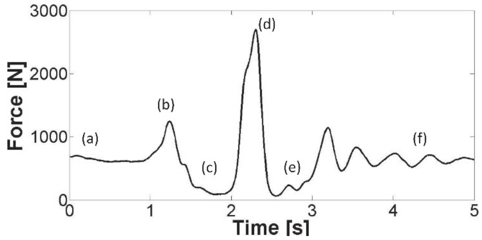


Figure 2. Force signal of the dislock movement: letters (a) to (f) refer to the images in the Figure 1.

the signal, the force only represents the weight of the performer (around 640 N here) as the weight of the rig is not considered. The force signal usually includes two major peaks: the first one occurs when the acrobat kicks (b) and the second one occurs when he passes through the vertical axis with his feet downward (d). Between and immediately after the two major peaks, the force signal has a value close to zero. The acrobat does not pull on the straps during the descending and ascending phase (Figure 1 and 2 (c) and (e)). Additional oscillations can appear as in Figure 2 when the acrobat has returned to his initial position as he bounces lightly (f). Not every participant generated these oscillations as all of them did not rebound after the final position has been reached. The signal analysis focused on the first two peaks.

Data collection

A load cell (Futek, LCF455 - 2000lbs) is mounted between the steel cable and the straps (Figure 3). The output signal is transmitted through an emitter (National Instrument, WSN 3214) to the receiver (National Instrument, WSN Ethernet Gateway). Force data is sampled at 100 Hz. A few tests with a higher sampling frequency of 250 Hz were done with a circus performer in straps, to make sure that 100 Hz is sufficient to capture the sharp peaks in the signal. In the preliminary tests, it was confirmed that time signals at 250 Hz and 100 Hz were in good agreement. A camera (National Instrument, Basler IP) operating at 25 Hz captured the performance on video. Film and force data were synchronized via a trigger in the Labview program.

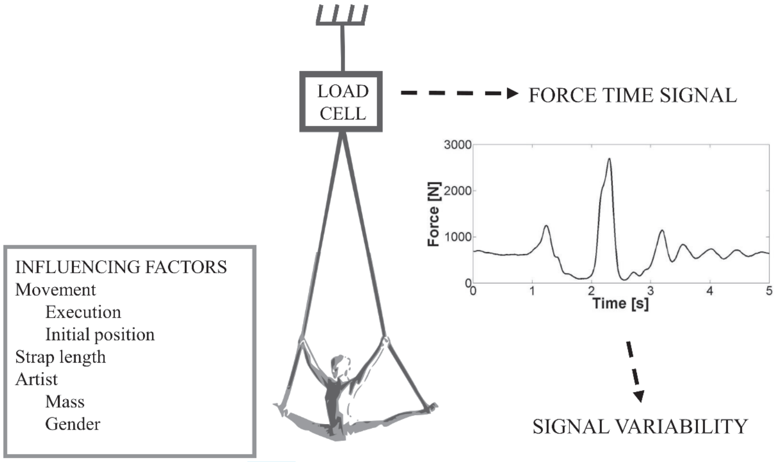


Figure 3. Summary of the study representing the location of the load cell, a list of the influencing factors and a force signal curve.

The load cell sensitivity was set with the certificate of calibration from the supplier. Static calibration was also performed every week using weights of 45.4 kg and 90.7 kg to quantify the measurement error. The load cell was tared once the straps were hanged so that only dynamic forces exhibited on the performer and the rig with the artist's weight are considered.

Over the course of six weeks, six participants performed the dislock movement once or twice et the end of class periods. Unfortunately not everyone could follow the procedure over the full duration of the study (because of injury or training for their final exam). At the end, each participant had performed the movement five to ten times. An aerial strap coach from the National Circus School watched all video recordings and ranked each performance with regards to their technical performance (for the study of influencing factors presented in *Influencing factors*) and each acrobat with regards to the movement variability (for the study of repeatability presented in *Statistical procedures*). **The coach participating in the study was trained through the National Circus School trainer program, which covers biomechanics among other topics. Since completing this training in 2009, the coach has trained 14 students in duo and solo trapeze, duo and solo aerial straps, silk, aerial hoop and rope. Seven of**

them won medals in Cirque de Demain and Young-Stage festival. The Cirque de Demain festival is the most prestigious circus competition in the world.

Data analysis

Signal processing As no kinematic analysis is conducted, it is impossible to determine at what point the movement starts from the force signals. To compare signals and to be able to measure their repeatability, it is necessary to superimpose them. Accordingly, a procedure is defined to time-shift signals to enable comparison.

Cross correlation is used to find and translate signals with respect to time, in order to reach the best similarity. The correlation between two signals generated by the same artist performing the dislock movement in the time domain can be defined as:

$$c_{p,m/p,l} = \sum_{i=1}^{N} f_{p,m}^{i} \cdot f_{p,l}^{i} \quad , \tag{2}$$

where $f_{p,m}^{i}$ is the force signal value at time t^i for $t = t^1, t^2, ...t^N$, for participant p when performing the dislock movement for the m^{th} time and $c_{p,m/p,l}$ is the correlation value between signals $f_{p,m}$ and $f_{p,l}$. A Matlab program shifts one signal with respect to the other until it maximizes the correlation value. This represents the timing of best similarities between the signals. The cross correlation technique was used to synchronize the different force data from the same acrobat, but not to synchronize the video recording with the force data.

Statistical procedures Once the shifting is done by maximizing $c_{p,m/p,l}$, three statistical methods are employed to quantify the repeatability of force signals.

The first method is related to the standard deviation. As explained in the introduction, the standard deviation is often used on one variable for a given time. As temporal force signals are compared, the standard deviation of the different signals for a participant are time-averaged. The temporal force signal contains the total duration of the movement.

The second method is the intraclass correlation (ICC). The ICC coefficient is calculated for one artist at a time. In the present study, according to Equation 1 presented in the introduction, σ_s^2 is the variance between force values at a given time and σ_d^2 is the variance between trials.

The last parameter calculated to estimate the repeatability of the force signals is the root mean square error (RMSE). The RMSE for participant p is defined as:

$$RMSE_p = \sqrt{\frac{1}{N(M-1)^2} \sum_{m=1}^{M} \sum_{l=1, l \neq m}^{M} \sum_{i=1}^{N} (f_{p,m}^i - f_{p,l}^i)^2} \quad , \tag{3}$$

where $f_{p,m}^i$ is the force signal at time t^i, as participant p performs the dislock movement for the m^{th} time, and where M is the total number of times participant p performed the movement.

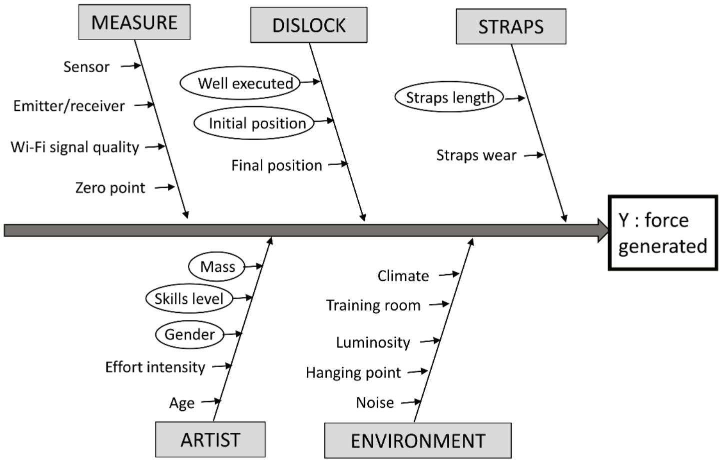


Figure 4. Cause-and-effect diagram of the force signal generated at the hanging point. The factors considered in this study are circled.

Influencing factors Analysis of variance (ANOVA) is used to evaluate the statistical significance of selected input parameters on the force signal 2. A distribution of the variability estimates can be represented using a Pareto chart. The Ishikawa cause-effect diagram in Figure 4 summarizes the parameters that may bring variability to the force signal. The list of parameters is not exhaustive. As no kinematic measurement was done, it was therefore decided that the technique behind the movement (e.g., speed of movement, body position changes throughout the rotations) is implicitly included in the parameter "well executed" dislock. The five parameters selected for the analysis are circled in Figure 4 and highlighted in Figure 3. Parameters encompassing the measurement, the environments and the strap wear or the effort intensity are difficult or impossible to measure; nevertheless, best efforts were made to control these parameters and make sure they remained constant throughout the study. The final position was not considered because it was identical for all measurements. All participants were between 18 to 21 years old so the age was not kept for the analysis. Skill level and the quality of execution are closely linked. A better skilled acrobat performs the movement better than a less skilled one. The dependence between the two parameters was shown by a Pearson's chi-squared test. Therefore, only the parameter "well executed movement" was kept for the analysis. The five parameters selected for the study vary greatly from one acrobat to another. If they have an influence on the force signal, knowing their relation may help coaches, technical riggers or the stage director to make guided choice in terms of performance, technical equipment or production.

The range of values of the chosen parameters was determined by the studied group of participants. Mass ranged between 59 and 72 kg. The total number of samples is 47 but it is not equally distributed among

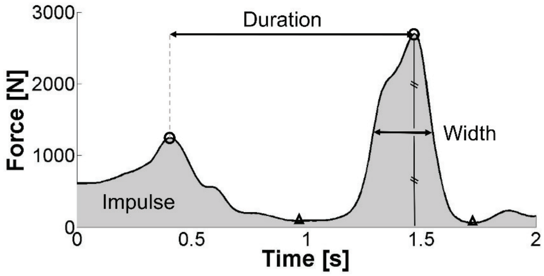


Figure 5. Force signal of the dislock movement with highlighted outputs for the ANOVA analysis: the duration between the two peaks, the width of the second peak at half of the maximum amplitude, and the impulse. Symbols ❍ indicates the two maximal force peaks, and △ indicates for the two force minima.

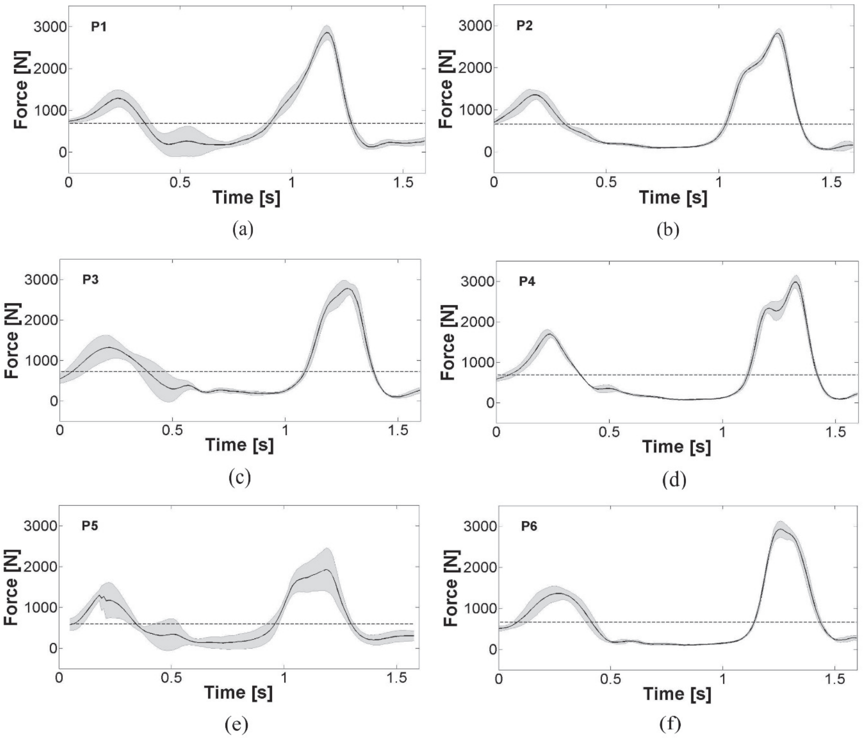


Figure 6. Average force signals in solid line, standard deviation as a grey surfaces and weight in black dashed line for the six participants: (a) P1; (b) P2; (c) P3; (d) P4; (e) P5; (f) P6.

the participants. The movement was started in two different positions: the first position was a handstand pike and the second one was a vertical handstand which turns into pike position. Thereon, the movement was continued the same way for both cases. The participants performed with six different pairs of straps which have different lengths, depending on what they preferred or what was available at the school. The different strap lengths were 3.03 m, 3.27 m, 3.87 m, 4.17 m, 4.83 m and 4.89 m. The parameter “well executed” was determined by a coach of the National Circus School and took three values: “very well executed”, “averagely-well executed” and “improperly executed”. **A scale limited to three possible values makes the assessment of the coach consistent. The resolution (3-value scale) is similar to the other considered parameters.** The features presented in Figure 5 for the analysis of the influencing factors were selected on the temporal force signal. They are: two maximal values of the force (❍) and the two minimal values of the force (△), the maximal loading rate at the initial rise of the highest peak, the duration between the two peaks (duration), the width of the second peak at half of the maximum value (width) and the impulse which is the area under the whole curve (Figure 5 for the three last feature). The length of the signal for the analysis is the same for each participant and adjusted to have all the necessary information in it.

Results

Mean value of the signals

The averaged force signal of each participant is shown in Figure 6 along with its standard deviation. The mean signal is represented with a full line, whereas the standard deviation with respect to time is presented as a shaded surface around the mean signal. The weight of the artist is also shown for reference (dashed line). The general shape of the average force curve is similar for all participants. The maximal value of the average force is relatively the same, ranging between 4.6 and 4.8 times the weight of all participants, except for P5 where a value of 3.9 times his body weight is observed. The duration between the two peaks varied from 0.93s to 1.09s for all participants. The shape of the larger peak is different depending on the participant: P1 has a sharper peak; P3, P5 and P6 have a rectangular shaped peak; and the peaks of P2 and P4 form a double wave. Significant variability is visible in the first peak for P1 and P3 and in the whole curve for P5.

Repeatability of force signals

Figure 7 presents the RMSE (a); the standard deviation (b); and the ICC (c) for each participant P1 to P6. They are viewed in relation with the ranking of the coach on the vertical axis: the number 1 means that the coach ranked the performer best. A lower value of the RMSE and the standard deviation, and a higher value of the ICC means a better repeatability of the signals. In Figure 7 (a), the RMSE increases monotonically with the ranking provided by the coach, showing excellent agreement. In Figure 7 b, better

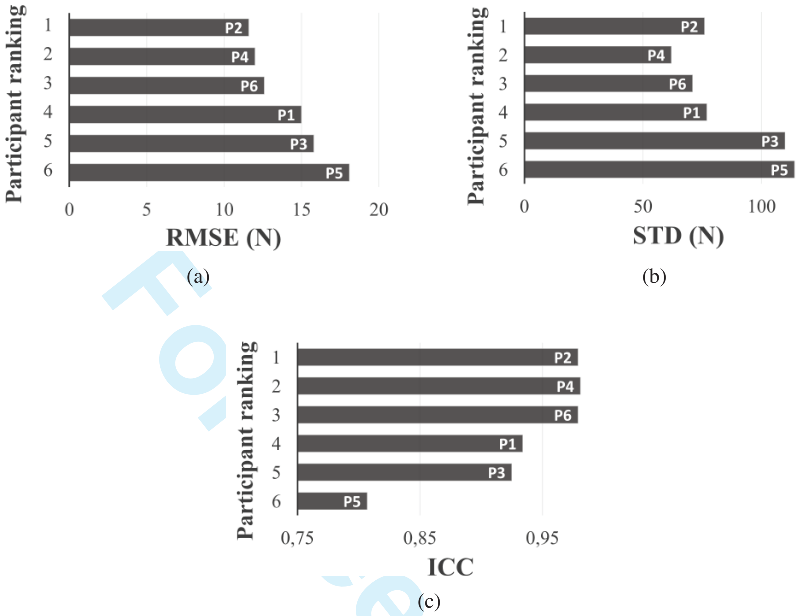


Figure 7. The relationship between the participant ranking by the coach and the RMSE (a); the standard deviation (b); and the ICC coefficient (c) for all participants.

ranked participants generally obtain lower standard deviations, also showing good agreement with the coach's ranking, except for participant P2. Likewise, the better ranked participants obtain higher values of ICC. Again, participant P2 breaks the trend slightly. The ranking determined by the RMSE method is the one in total agreement with that of the coach. According to Bartko's classification[21], high levels of repeatability were identified for all participants ($ICC \geq 0.8$ in Figure 7 (c)) indicating that they all performed the dislock movement with little variability.

Influencing factors

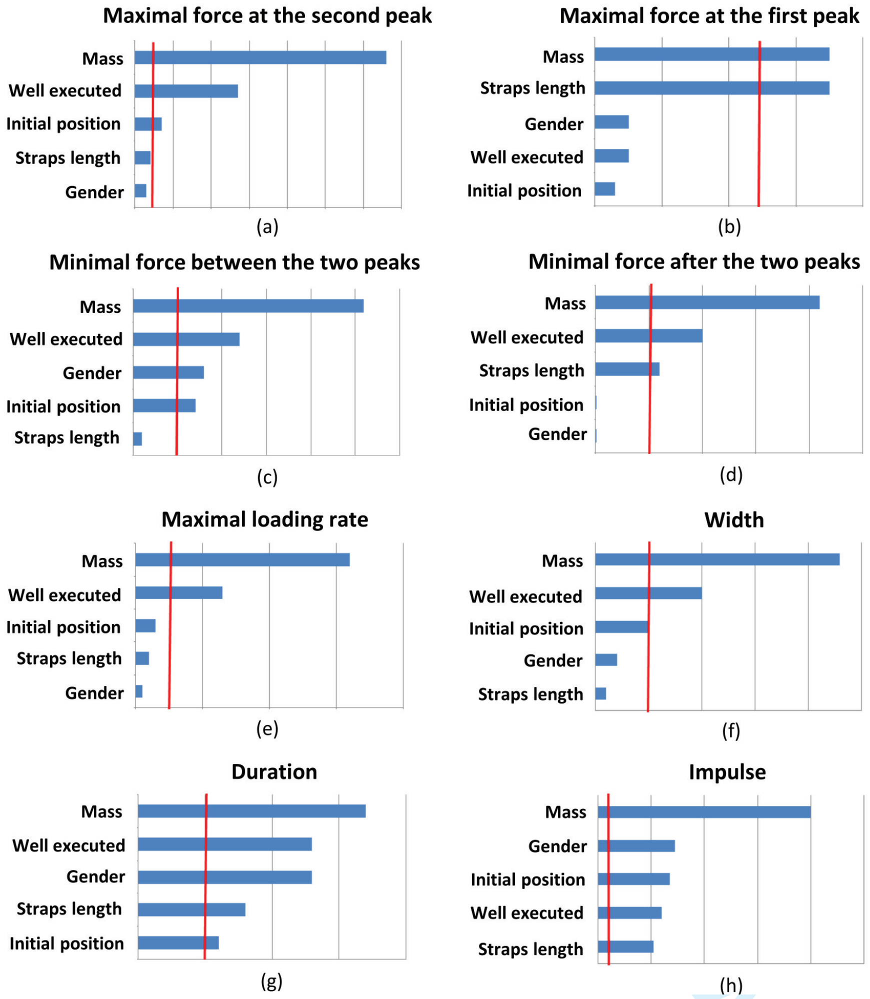
Pareto diagrams show the relative importance of each output parameter with respect to the mass of the artist, the gender, the initial position of the movement, the length of the straps, and whether it was performed properly or not (Figure 8). The red vertical line represents the level of significance beyond which parameters can be considered to have an effect on the force signal. It appears that the mass is clearly the most influencing input parameter on the force signal parameters, both on the amplitude and the time characteristics. A well-executed movement is also influential, but not for all output parameters. Its influence particularly concerns the duration between the two peaks. It is difficult to state on the influence of others parameters such as the gender, the straps length or the initial position.

Discussion

The aim of this study was to investigate the variability of circus artists doing the dislock movement in aerial straps through the analysis of the repeatability of tension force signals measured at the hanging point. Three statistical methods were used and compared to the rankings of a circus coach. The goal was to determine if a circus coach could use a tool to determine the variability of a circus artist, and thus the artist's mastering of a sequence, through the analysis of the force signals.

It is found that statistical methods can be used to estimate the repeatability of force signals generated by circus artists and are in good agreement with the assessment of the coach. The RMSE method fared better in terms of agreement with the ranking of the coach. The force variability for each participants seems to be greatest around the two peaks (Figure 6), because, as explained by the circus coach, they are key moments in the movement. The first peak occurs when the acrobat kicks and a wrong orientation of the feet can have disastrous consequences on the success of the movement (Figure 1). The second peak occurs when the acrobat passes through the vertical axis. At that time, the acrobat must give himself sufficient momentum to return to his initial position (Figure 1). It is important for him to have the right timing for this momentum if he wants to finish the dislock movement with success. However, the fact that all participants performed the dislock movement very well makes it difficult to strictly discriminate the methods. It is also acknowledged that the number of participants and the number of movement repetitions were small. More data and more disparities in skills level would allow confirming the proposed method.

The use of cross correlation to time-shift signals to maximize the similarity influences the results on the evaluation on repeatability. This method gives more weight to parts of the signal with more amplitude



Maximal force at the second peak

(a)

Maximal force at the first peak

(b)

Minimal force between the two peaks

(c)

Minimal force after the two peaks

(d)

Maximal loading rate

(e)

Width

(f)

Duration

(g)

Impulse

(h)

Figure 8. Influence of input parameters on the maximal force of the second peak (a); on the maximal force of the first peak (b); on the minimal force between the second peak (c); on the minimal force after the peaks (d); on the minimal loading rate (e); on width (f); on duration (g); and on impulse (h).

and thus will try to match the largest peak, the second one of each signal, together in time. That would explain why greater variability is found on the first peak in Figure 6, due to varying delay between the first and second peaks.

The hypothesis that the indirect measurement (force signal) provides information about the movement variability without a direct measurement of movement kinematics seems reasonable, since the results agreed with the ranking of the coach. However the analysis of variability of an acrobatic movement through the repeatability of force signals does not give complete information about the quality of execution. An indirect measure, which is in this case the axial force of the hanging point, misses a lot of information about the technical performance. For example, an acrobat who is doing the movement with a bad technique, but who is doing it every time the same way, will have good results at repeating the force signal. A thorough evaluation requires the analysis of biomechnical parameters to know if a movement is well performed or not. The ideal approach to analyze movement variability would have been to conduct a detailed kinematic analysis alongside the force transducer analysis to more directly link movement to kinetic effects. However, as explained in the Introduction, direct measure of movement kinematics is not practically feasible in coaching situations. **In the future, the method could be employed to measure the variability of movement execution in circus disciplines in which forces can be measured. The method could be very useful in the case of an artist who trains alone or if the coach cannot supervise the acrobats constancy. At the National Circus School, to know if it is safe for an artist to perform a movement, the coach asks the artist to perform it three times in a row. If the artist succeeds to perform it well, he is considered ready to perform it in an assessment or in a show. The same method could be employed with a tool measuring the variability.**

It has recently been shown that more functional variability occurs in the upper parts of the rotation whilst elite gymnasts execute giant circles[25]. The force data of the dislock movement do not seem to correlate well with this finding since the maximum variability is observed when the acrobat swings below the rig. Nevertheless, there is still variability in the better ranked acrobats (Figure 6 and 7). The coach explained that too much variability can be dangerous, specially when the acrobat kicks. A bad orientation of the feet can have disastrous consequences on the success of the movement. If the acrobat kicks too high, it is more difficult to control the descending phase and the movement will seem heavy and not aesthetic. If the acrobat kicks too low, he puts himself in a dangerous situation, where he has little time to rotate his shoulders, which increases the risk of dislocating the shoulders. The students are trained to accomplish the movement successfully regardless of the orientation of the feet, as long as the orientation does not put them in danger. That may explain why the coach ranked participant P2 less variable than the participant P4. Participant P2 has more variability during the first peak in Figure 6, but he still succeeds to finish the movement properly.

A higher frame rate of the camera system could allow determining the exact time of the kick, using biomechanical parameters. The different shapes of the larger peak showed in Figure 6 are probably due to the timing of the impulse which propels the acrobat up. Based on the shape of the curve, hypothesis can be made on the timing of the impulse required to come back to the initial position, against the timing when the acrobat passes through the vertical axe (Figure 1 (d)). For example, P1 seems to initiate his impulse at the same time as he passes through the vertical axis because the peak is sharper (Figure 6 (a)). The rest of the participants appear to provide their impulse before or after they pass through the vertical axis: the peak has a rectangular shape or a double wave. Additional work would be necessary to validate this hypothesis. Force signal analysis could eventually be used as a tool to evaluate not only the repeatability but also the quality of the technique.

An ANOVA analysis was used to determine the importance of the chosen parameters on the force signal, including: the mass and the gender of the artist, the length of the straps, the initial position and the quality of execution. It makes sense that the mass and the quality of execution are the most influential parameters. Mass and force are obviously linked through acceleration inertia. Furthermore, a more or less successful performance has an impact on the shape of the curve. Depending on the angle at which the artist extends his body (Figure 1 (b)), the duration of the force and the maximal amplitude will change. If the artist kicks his legs too high, the body will fall back down harder during the descending phase, which is not desirable during performance. On the other hand, if he kicks his legs too low, it places him in a dangerous situation because he has little time to rotate his shoulders. **The number of scale points for each of the parameters is somewhat limited. The initial position and the gender parameters**

are on 2-points scales, the "well-executed" parameter is on a 3-points scale, the mass is on a 4-points scale and the straps length is on a 6-points scale. Therefore a significant relationship might not have emerged between a given parameter and the force outputs due to the lack of sensitivity. In particular, the choice of a 3-points scale for the parameter "well executed" aimed at facilitating assessments by the coach. Even though a strong influence of this parameter was observed compared to other parameters, additional points might have increased the sensitivity with respect to the force outputs. In addition, it is also clear that another parameter that is not taken into account may have a major influence: the elastic reaction of the hanging equipment and the hanging point to ceiling. Characterizing and taking into account the mechanical properties of these structures would help completing the analysis.

Conclusion

In conclusion, the performance of circus acrobats is found to be very consistent in the dislock movement. Out of the three methods tested, the statistical method that is in better agreement with the rankings of the circus coach is the mean value of the RMSE. Movement variability in sport usually is measured through the analysis of kinematic variables. This work shows that movement variability can also be assessed by the analysis of force signals or any signal that characterizes the movement. This is really helpful in situations where it is not convenient to conduct kinematic measurements, which is often the case in circus. In the future, the method could be employed by coaches to measure the variability of movement execution in circus disciplines or others sports and activities in which forces can be measured. Science and technology will definitely be part of circus training. Performance analysis and theoretical work will be required to help coaches and artists to improve performances. For now, this analysis does not give complete information on the quality of performance. With more research, an algorithm coupled with the load cell may be able to do a movement analysis in real time. Such machine learning algorithm could be trained with some data where the coach would have assessed the performance, then the features would automatically be selected by the algorithm. A software program would be able to advice on how to improve the movement.

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