INDIRECT MEASUREMENT OF FORCES ON THE GYMNASTICS RINGS

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INTRODUCTION: Forces produced during the Men's Gymnastics Rings Exercise have been investigated to help identify factors within a rings performance which are associated with excellence, and patterns in technique which affect the incidence of injuries. Patterns of force inherent in the skill, which were associated with the degree of expertise of the performance were identified by Sale and Judd (1974), and Chapman and Borchardt (1977). Forces up to eleven times the body weight at the bottom of a longswing, were recorded by Nissinen (1995). Nissinen however argued that it is not so much the magnitude of the peak force that is dangerous for the gymnast, it is much more the pattern of the force. Dramatic differences between gymnasts in the force curves during the bottoming phase of the dislocate were detected by Cheetham et al. (1987) which highlighted that gymnasts displaying a two peak force curve may be more prone to injury. Cheetham et al. also mentioned that the differences in technique were not obvious on the video, illustrating that without the combination of force data with video recordings the ability to detect components of technique essential for excellence, or faulty techniques which may eventually lead to injury, is much reduced.
Methods to record the forces applied by gymnasts have used load cells either positioned within the metal framework of the rings at the attachment of the ring cable or connected in series between the ring cable and the frame. The purpose of this study was to develop an indirect video based method for determining the forces exerted on the rings during a gymnastics exercise, which does not require modification of the rings apparatus.
Federation Internationale De Gymnastique (F.I.G.) specifications state that the rings apparatus must contain a device located at the cable suspension points which provide elastic damping. The elastic damping suspension device used in this study (Continental Sports Limited), referred to as the 'bungs', comprised a set of concave metal washers which progressively flatten under loading. When the gymnast swings downwards on the rings, downward movement of the rings frame and deformation of the 'bungs' occur. The manner in which the frame and the 'bungs' responded to applied loads was hypothesised as being able to provide sufficient information to indirectly determine the forces exerted on the rings.

METHODS: Two genlocked video cameras (Sony Hi8 Hyper HAD model EVW-300P and Panasonic CCD F15) were used to record a series of swinging skills performed by a member of the Great Britain Senior Men's National Team (67.9 kg, 1.71 m). A third genlocked video camera (Sony video Hi8 Handycam PRO model CCD-VX1E) recorded a close-up view (field of view approximately 0.8 meters wide) of the displacement of the top of the rings frame and 'bungs', with an electronic 1/300s shutter at 50 fields per second. The camera was located a distance of 10.84 m from the center of the rings frame, 3.85 m below the height of the 'bungs'. A strain-gauged load cell (type FCA-3, 90 degree biaxial rosette, 120 Ohm foil gauge, gauge factor 2.1, Techni Measure Limited, bonded to both sides of a mild steel plate), was fitted into one of the rings cables to directly measure the applied forces for calibration and evaluation purposes. The signal from the load cell was amplified (CIL Worthing amplifier, model SGA1102), and fed into the input terminals of a CED1401 analogue to digital converter (ADC), where the signal was sampled at 1000 Hz. A manual trigger initiated the recording of the load cell signal and simultaneously set off two light emitting diode (LED) units which enabled the load cell data to be synchronized with the video data to within one millisecond.

Fourier analysis was applied to the load cell data to improve the signal to noise ration. A truncated Fourier series with the cut-off frequency set to 46 Hz was used. The smoothed data were reconstructed in the time domain using an inverse Fourier transform. A residual analysis of the difference between filtered and unfiltered signal was carried out for a range of f_cs, to ensure an optimal f_c was selected.

Prior to the main recording session, static calibration loads were applied to the rings and synchronized video recordings of the frame and 'bung' deflections were recorded to establish a relationship between the applied force and the resulting frame and 'bung' displacement. Load was applied to the ring cables by hanging weights from both rings. The load was increased in intervals up to a maximum of 6kN. A total of 38 calibration trials were recorded, consisting of two trials for each load value.

All video data were obtained using a Target high resolution video digitizing system. To improve the accuracy of the identification of frame and 'bung' location during digitizing, a white sphere 24mm in diameter was attached to the top of both 'bungs' and two white spots 19mm in diameter were placed on the rings frame directly beneath the sphere. Frame displacement data were obtained from the digitized spot locations. The displacement of the sphere represented both the deformation within the 'bungs' and the frame displacement. 'Bung' displacement was calculated by subtracting the frame displacement value from the corresponding value of sphere displacement.

The Direct Linear Transformation was used to reconstruct the 3D coordinates of the gymnast's joint centers and the orientation of the rings cables from the two main camera views. Force values recorded during a series of backward longswings, forward longswings and basic swings by the gymnast were obtained indirectly from digitized video data of the frame and bung displacements, and were compared to the force values obtained directly from measured strain gauge output in order to evaluate the indirect method.

RESULTS AND DISCUSSION: During calibration the displacement of the rings frame was linear, with a displacement of 10.4 mm resulting when the maximum load of just under 6 kN was applied to the rings. Each 'bung', which provides the F.I.G. required damping, displayed a non-linear relationship up to a maximum displacement of 19.4 mm at a submaximal applied load of 4690 N. No further displacement occurred in the 'bung' as the load was increased. The estimated error in digitizing the location of the frame and 'bungs', based on the standard error of the vertical coordinate for the spot and sphere locations over ten adjacent fields in the static calibration trials, were 0.13 mm and 0.18 mm respectively.

Two mathematical functions, which accurately reflected the differing behaviours of the linear spring (the frame) and the damped spring (the bung), minimizing the differences between the known displacement measured in the static load calibration trials and the displacement determined by the function, were fitted to the

static calibration data using a simulated annealing procedure. The root mean squared difference (RMSD) between the known displacement measured in the static load calibration trials and the displacement determined by the functions fitted were 0.22 mm and 0.21 mm for the frame and 'bung' respectively.
The digitized frame and 'bung' displacement data required the rings frame to remain in the vertical plane in order to indirectly obtain accurate force values. However, during the series of swings performed by the gymnast a substantial amount of frame sway occurred (top of frame moved a maximum of 42 mm towards the close-up camera, during the backward longswing) following the bottoming phase of the swings. Due to the close-up camera being located below the level of the 'bungs', a systematic error in the displacement values resulted. The measured values of frame and 'bung' displacement were therefore corrected taking into account the swaying of the frame. Frame and 'bung' displacement data were not adjusted during the initial second of each performance as this time period corresponded to recordings prior to the bottoming phase of the swing.
The level of frame sway was determined by digitizing the location of the top corners of the rings frame. Fourier analysis was applied to the frame coordinate data to reduce the level of noise. However, residual errors in the frame displacement data limited accuracy in the latter part of each trial. The indirectly determined force values were also adjusted to take into account the orientation of the rings cable relative to the vertical.
The RMSD between the measured and predicted force values, and %RMSD (RMSD expressed as a percentage of the range of the force values), for a backward longswing, forward longswing and basic swing are listed in Table I for both the entire duration of the swing, and for the initial one second of each swing.

Table I RMSD and %RMSD between force values obtained using the direct (load cell) and indirect (video based) methods for each cable

	Backward Longswing	Forward Longswing	Basic Swing
Peak Force (N)	2481	2448	1766
RMSD calculated over the entire duration of the swing.			
RMSD (N)	133	163	114
% RMSD	5.4	6.7	6.5
RMSD calculated for only the first second of the swing.			
RMSD(N)	45	63	37
% RMSD	1.8	2.6	2.1

The level of accuracy of the indirect method was largely dependent upon whether the frame sway correction was applied. Although frame sway is an unavoidable consequence of the performance of dynamic movements, accuracy of the indirect method throughout the full range of each movement could be significantly increased by altering the location of the close-up camera to avoid parallax errors. The %RMSD values for the first 1 second of the trials were representative of the accuracy of the indirect method, with values in the order of two percent of the force range.

CONCLUSIONS: It was concluded that the indirect method, based on video digitization of the deflections in the suspension frame and 'bungs', provided data which matched the overall profile of the force-time histories in the rings cables. The indirectly determined force-time traces for the three swings closely resembled the force-time traces obtained from the directly measured strain gauge output. A feature of the indirect method was it's ability to detect small but distinctive characteristics of the force-time trace. As the gymnast approached the bottoming phase of the swing in a backward longswing, a distinctive 'kink' was evident, which Nissinen (1995) suggested could be used to distinguish better performers, and Cheetham et al., (1987) concluded gave an indication of a gymnast's potential for injury. The indirect video based method was able to estimate cable tension to an accuracy of approximately 2 percent of the overall force range. With this level of accuracy, the method is able to provide detailed information on the forces exerted on the rings during gymnastic movements performed in competition, thereby enabling the identification of those components essential for excellence or those aspects of the technique that could lead to an increased risk of injury.

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