Analysis of segmental kinetic energy in cricket bowling

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Abstract

Fast bowling in cricket is an athletic motion requiring the coordination of multiple body segments in order to release a ball at high speed. The application of the kinetic link principle to bowling proposes that the optimal coordination of movement actuation follows a proximal to distal sequence, allowing the systematic and progressive transfer of angular momentum from the larger, heavier body segments to the smaller distal segments. An analysis of segmental kinetic energy potentially provides information on the order of segmental sequencing and the effectiveness of energy transfer between the segments throughout the kinetic link chain. However, there has been no calculation of segmental kinetic energy in cricket fast bowling. In this study, 34 fast bowlers (22.2 ± 3.9 years) of premier grade level and above were tested using a three-dimensional motion analysis system (240 Hz). Based on the range of measured balls (27.0 m s⁻¹ to 35.6 m s⁻¹), the sample was divided into four speed group categories: slow-medium, medium, medium-fast and fast. With exception of the fast group relative to medium-fast group, each faster group tended to have higher segmental kinetic energies. Although there were no clearly discernible sequencing differences between bowling speed groups, the temporal occurrences of peak segment kinetic energies showed that bowlers exhibited a general order of proximal to distal sequencing with the larger heavier proximal segments having the highest energy and activated first. In general, there is an approximate proximal to distal sequence in cricket bowling, which indicates that bowlers of varying speed levels first produce high kinetic energies in their trunk segments before circumducting the bowling arm during the acceleration phase.

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1. Introduction

Cricket fast bowlers attempt to coordinate the motions of multiple body segments to propel a ball at high speed. A fundamental biomechanics principle that governs the motion of a system of multiple linked body segments, is that the magnitude, distribution and transfer of kinetic energy are determinant factors in the generation of end-effector speed. For instance, according to the kinetic link principle, a proximal to distal sequencing of body segments will produce a mechanical advantage by sequential transferring the energy from the heavier and stronger proximal segments to the lighter and weaker distal segments [1]. By means of the conservation of energy and momentum, these smaller distal segments will end up with relatively high velocities owing to their lower masses and moments of inertia.

Although there are some exceptions in the ideal proximal to distal sequencing scheme, such as the timing of humeral and forearm long axis rotations in tennis serving [1] and throwing, the evidence shows that in comparative movement sequences in which a single hand is utilised as a high-speed end-effector the order of activation is generally pelvis, upper trunk and arm segments. Previous biomechanics research on fast bowlers in cricket has only studied the temporal order of motion in terms of kinematics. It has been found that the timing of pelvic rotation occurs before front foot contact when the ball is at its lowest point in the pre-release bowling arc [2]. In addition, for most of the period from front foot contact to ball release, pelvic rotation precedes shoulder rotation [3]. However, the most appropriate quantification of segmental sequencing as defined by the kinetic link principle is in terms of kinetic energy, which has not been calculated in cricket bowling.

The application of the kinetic link principle to cricket bowling suggests that a proximal to distal ordering of segmental movements is mechanically advantageous in cricket bowling. Therefore, the aim of this study is to examine the distribution of segment kinetic energy and temporal differences between the occurrences of peak segment kinetic energies. The hypotheses are that (i) the large segments will have the highest segment kinetic energies and (ii) the timing between peak kinetic segment energies will reveal a general proximal to distal sequence.

2. Methods

2.1. Sample

Thirty-four male bowlers (22.3 ± 3.7 years) were recruited from competition levels from premier club standard and above. The bowlers were divided into four speed groups: slow-medium (27.8 – 30.6 m/s); medium (30.6 – 31.9 m/s); medium-fast (31.9 – 33.3 m/s); fast (> 33.3 m/s) [3]. All reported that they were free from any injury during the data collection sessions. Ethics approval was obtained from the human research ethics committees of the University of Auckland and the University of Waikato.

2.2. Data collection

The trials were performed in a biomechanics laboratory, which permitted a 20m length run-up. An 8-camera EVa Motion Analysis System (Motion Analysis Corporation Ltd., USA) was used to capture three-dimensional motion (240 Hz) and force plate (960 Hz) data on six trials for each bowler, while front and rear foot contact were made on two Bertec 6090 force plates. Each subject was instructed to bowl at maximum effort and pitch the ball within a ‘good length’ area demarcated by two white lines 15 and 19m from the stumps at the bowler’s end. Subjects had also to rate their performance from 0 to 10 using an analogue performance scale. The capture volume encompassed the back foot contact, front foot contact, ball release and follow-through phases of the bowling action. The EVa motion analysis system was...
calibrated according to the manufacturer’s recommendations resulting in a residual error of marker position of less than 2 mm.

Motion analysis capture was performed on each subject wearing a full body marker set comprising forty-five 25 mm spherical markers, which were attached to bony landmarks [3]. Markers were located on the left and right sides of the body except for markers placed half-way between the posterior superior iliac spines (mid-PSIS), and on the 7th cervical vertebrae, supra-sternal notch, T10, sternum and the head. Most marker positions were chosen to define joint centres to delimit segment lengths as listed in [4]. Exceptions were the position of the shoulder, mid-trunk, hip markers and cricket ball. The positions of the anterior superior iliac spine (ASIS), mid-PSIS and greater trochanter markers were as recommended by [5], who used the positions of these markers to calculate the hip joint centres. All other joint centres were calculated as the average position between two markers placed either medially and laterally or anteriorly and posteriorly on the joint.

2.3. Fifteen-segment rigid body model

From the xyz-coordinates of the marker positions and calculated joint centres, local segment coordinate systems were defined at the centres of mass of each body segment using the standard approach of [6]. The orientations of the joint coordinate systems were specified by $zxy$ Euler angles. Both the location of the origins and the orientations of the joint coordinate systems were imported into a program written in the Mechanical Systems Pack (Dynamic Modeling), which is a set of packages designed in Mathematica (V. 5.2, Wolfram Research Ltd.) to assist in the analysis and design of spatial rigid body mechanisms. Using the library of 3-D geometric constraints, a 15-segment model of a cricket bowler was created with anthropometric and inertial properties from [4] (mass, centre of mass, and moment of inertia) and joint coordinate systems for each segment. The segments were linked together using Newtonian constraint equations and solved iteratively using the Newton-Raphson method [7]. The velocity of the segmental centre of mass and the angular velocity were calculated from the kinematic data was fed into the model as input. A recursive fourth-order low-pass Butterworth filter was used to smooth the kinematic data. The cut-off frequencies were determined from the Fast Fourier Transform analysis functions in Mathematica (Version 5.2). The kinetic energy of each segment was calculated as the components of translation and rotation kinetic energy [8]. Translation and rotation kinetic energies were calculated for all the body segments: foot, shank, thigh, lower trunk (pelvis and lumbar spine), upper trunk (thoracic spine), upper arm, forearm and hand. Other parameters calculated were: (i) relative segment kinetic energy, which was the mean segment kinetic energy calculated as a percentage of the total body mean kinetic energy and (ii) comparative percentage increase of mean segmental kinetic energy between adjacent bowling speed groups.

3. Results and Discussion

Most of the kinetic energy produced by the bowling action was translational. The mean rotation kinetic energy for the upper arm, forearm, upper trunk, and lower trunk was a small percentage of their corresponding translation kinetic energy (fast group): 3.9%, 1.7%, 15.4%, and 8.7%, respectively. Similar percentages were found for the other bowling groups. By expressing segmental kinetic energy as a percentage of the total body energy, the kinetic energy distribution of the translation and rotation energies could be clearly seen (Figure 1). Most energy was expended in the translatory motions of the larger segments such as the lower trunk, upper trunk and thigh segments. The smallest kinetic energies were rotational. Even the rotation energy of the trunk segments was less than 2% of the total energy expended. The rotation energy of the bowling arm was less than 0.5%. However, these percentages do
not reflect the importance of these motions. The moments of inertia of these segments, particularly those of the bowling arm are small, and even small rotation kinetic energies, especially about the longitudinal axes, can produce large angular velocities. A similar argument could explain the relatively small trunk rotation energies, despite the importance of trunk rotation in the bowling action [3].

Since both translation and kinetic energy are important in the delivery of a ball, the next purpose was to determine the overall pattern of segmental sequencing. To quantify this pattern, the temporal order of

Fig. 1. The segmental kinetic energy distribution from back foot contact to ball release for all bowling groups. Each segment’s energy was calculated as a percentage of the total body energy. Translation kinetic energy is shown for upper bowling arm upper bowling forearm, bowling hand, upper trunk (thorax), lower trunk (pelvis and abdomen), front forearm, front hand, head and neck, rear thigh, rear shank, rear foot. Rotation kinetic energy (ROT) is shown for bowling arm (bowling arm rot), forearm (forearm rot), hand (hand rot), upper trunk (upper trunk rot) and lower trunk (lower trunk rot). The energy distribution was remarkably uniform across bowling groups. Note that rotation energy refers to the total rotation kinetic energy of a segment, i.e. the sum of the rotation kinetic energies of a segment about each of its local body-fixed axes.

peaks in the segment kinetic energy curves was observed (Figure 2). The upper trunk and the lower trunk did begin with the largest translation energies through the initial momentum generated by the run-up. As front foot contact approached (i.e. at 51%), the translation kinetic energy of the front upper arm was the first to peak at 25%, followed by the lower trunk (peaking at 39%), which was subsequently followed a short time later by the upper trunk, which peaked at 46%. During the bowling arm acceleration phase (51-100%), the translation kinetic energies of the lower trunk, upper trunk and front upper arm were decreasing, whereas the rotation kinetic energies of the lower trunk and upper trunk were increasing. The lower trunk rotation kinetic energy reached a peak value (30.8 J) at 66%, which was closely followed by the peak value of upper trunk rotation kinetic energy at 72% (41.4 J). The translation kinetic energies of the bowling arm segments (i.e. upper arm, forearm, and hand) had started increasing just prior to front foot contact, but only reached peak values after the trunk rotation energies had dropped considerably. The bowling upper arm, forearm and hand reached their peak translation kinetic energies at 86%, 92% and 93%, respectively. Not shown in Figure 2 are the corresponding bowling arm rotation energies, which continued to increase reaching their peak values at approximately ball release. Therefore, generally, after
the initial raising and extension of the front arm, the general sequencing order for the bowling action was proximal to distal, starting from the lower trunk and working upwards, finally culminating with the motion of the bowling hand. Furthermore, the peak rotation kinetic energy of a segment generally occurred after its corresponding peak linear kinetic energy, and the rotation kinetic sequencing order was also from proximal to distal. However, in this study, there were no clearly discernible sequencing differences between speed groups (i.e. fast, medium-fast, medium and slow).

![Fig. 2. Kinetic energy of major segments in bowling action from back foot to ball release for the fast group. The curves are not drawn to time scale: 0% to 50% represents the delivery stride phase from back foot contact to front foot contact, and 51% to 100% represents the bowling arm acceleration phase from front foot contact to ball release. Note that in actual bowling, the bowling arm acceleration phase is shorter than the delivery stride phase. Translation kinetic energy is shown for the bowling upper arm, bowling forearm, bowling hand, front upper arm (i.e. non-bowling upper arm), upper trunk and lower trunk. Rotation kinetic energy is shown for the upper trunk and lower trunk. Rotation kinetic energy for the other segments was relatively small and not shown here. Note that rotation energy refers to the total rotation energy of a segment, i.e. the sum of the rotation kinetic energy of a segment about each of its local body-fixed axes.](image)

Generally, the kinetic energy expenditure of body segments increased with the speed of the bowling group. The mean total kinetic energy expended by the medium-fast group was 23.6% higher than the medium group. This was similar to 23.1% higher mean total kinetic energy expenditure of the medium group compared to the slow group. However, there was one exception: the medium-fast group expended 7.1% more mean total kinetic energy than the fast group. The extra energy was translation kinetic energy
expended mostly in the lower limbs, and not in those segments most directly concerned with ball speed generation. The fast group still expended more rotation kinetic energy in the bowling upper arm, bowling forearm, bowling hand, lower trunk rotation, and upper trunk than the medium-fast group. The most marked percentage increases in these rotation kinetic energies were of the lower trunk and upper trunk: 32.0% and 21.6%, respectively. Interestingly, the medium-fast group expended 16.0% more energy in the lower limbs than the fast group, but the fast group ended up producing 4.7% more kinetic energy from the motion of the entire upper body. Further research is needed to establish whether the kinetic energy of medium-fast group was either (i) not being transferred as efficiently up through the kinetic link chain as for the fast group, or (ii) was wasted on superfluous motion that did not contribute significantly to ball release speed. Furthermore, ball release speed divided by mean total body kinetic energy output may be a feasible measure of bowling efficiency.

4. Conclusions

Although there were some exceptions, this study showed that bowlers exhibited a general order of proximal to distal sequencing in kinetic energy. The larger and heavier segments, which were the proximal segments, had relatively higher segment translation and rotation kinetic energies than the smaller distal segments. As the bowling action progressed towards ball release, the kinetic energy of these proximal segments reduced and the kinetic energy of the lighter, distal segments subsequently increased. Such a sequencing scheme is consistent with the postulates of the kinetic link principle to efficiently actuate the motion of multiple body segments in athletic motions. Contrary to this hypothesis, there were no clearly discernible sequencing differences between speed groups. It needs to be investigated whether there would be a similar result if the bowling sample was strictly controlled for action type. However, apart from timing, the magnitudes of segment kinetic energy are also important for the generation of ball release speed. With exception of the lower limbs, each faster group tended to produce higher segmental kinetic energies. Further detailed analysis of segmental kinetic energy of bowling is required to determine the factors that contribute to mechanical efficiency. This would facilitate the ultimate task of cricket biomechanical engineers which is to develop fast bowling techniques that optimize ball release speed.

References

[1] Marshall, RN., Elliott, BC. Long-axis rotation: The missing link in proximal-to distal segmental sequencing, J Sport Sci 2000; 18:247-254.

[2] Mason, B.R., Weissensteimer, J.R., Spence, P.R. Development of a model for fast bowling in cricket. Excel 1989; 6(1): 2-12.

[3] Ferdinands, RED. Three-dimensional biomechanical analysis of fast bowling in cricket. Unpublished PhD Thesis, University of Waikato; 2004.

[4] de Leva, P. Adjustments to Zatsiorsky-Seluyanov’s segment inertia parameters. J Biom 1996; 29 (9), 1223-1230.

[5] Bell, AL., Pederson, DR.,Brand, RA. A comparison of the accuracy of several hip center location prediction methods. J Biom 1996; 23(6): 617-621.

[6] Grood, ES., Suntay, WS. A joint coordinate system for the clinical description of three-dimensional motions: applications to the knee. J Biom Eng 1983; 105, 136-144.

[7] Haug, E.J. Computer aided kinematics and dynamics of mechanical systems. Volume 1: Basic methods. Needham Heights, MA: Allyn & Bacon; 1989.

[8] Mansour, JM Lesh, MD., Nowak, MD., Simon, SR. A three dimensional multi-segmental analysis of the energetics of normal and pathological human gait. J Biom 1982; 15(1), 51-59.