DETERMINING THE DYNAMIC CONTRIBUTIONS TO KICKING FOOT SPEED IN RUGBY PLACE KICKING

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The purpose of this study was to determine the dynamic contributions of joint torques to the generation of kicking foot speed in rugby place kicking. Motion capture and ground reaction force data were recorded from three Japanese rugby players, who were instructed to kick as far and as straight as possible. Each kicker‘s whole body was modelled as a system of 15 rigid-linked segments. The major contributors were calculated using equations of whole-body motion, including consideration of the generating factors of the motion-dependent terms. The flexion torque at the kicking leg hip joint was found to be the largest contributor for all kickers; exerting large flexion torques at the kicking hip joint throughout the final aerial phase of the approach and the subsequent kicking action appears crucial for obtaining a large kicking foot speed.

KEY WORDS: induced speed analysis, motion-dependent term, cumulative effect, equations of whole-body motion

INTRODUCTION: Place kicking contributes 45% of all of the points scored in international Rugby Union (Quarrie & Hopkins, 2015). Because of this importance, kicking coaches are commonplace in Rugby Union but their technical coaching is based largely on experiential knowledge as a limited scientific biomechanical analysis of place kicking currently exists (Bezodis & Winter, 2014). Rugby place kicking is a whole body, three-dimensional, ballistic movement and various technical factors such as support foot placement (Cockcroft & van den Heever, 2016), upper body actions (Bezodis et al., 2007) and kicking leg joint kinematics (Sinclair et al., 2014) have therefore been described. However, as the primary aim in rugby place kicking is to achieve a high and appropriately directed kicking foot velocity at ball impact, it is imperative that the dynamic contributions towards this kicking foot velocity are quantified and understood. In a linked-segment system, the motion of the endpoint (such as the foot in a kicking action) is determined by the motion of the more proximal segments and the forces which act about the joints at each link in the system. These contributions include a term due to the sum of all of the joint torques, a motion dependent term (MDT) due to the centrifugal forces, Coriolis forces and gyroscopic effective moments, and a term due to the effects of gravity. Calculation of these dynamic contributions ultimately enables the determination of the functional role of specific joint torques based on whole-body, linked-segment equations of motion. Dynamic contribution analyses in other ballistic movements such as baseball batting have revealed that the MDT contributes considerably to the endpoint speed, and can exceed the contribution of the summed joint torque terms towards the point of ball impact (Koike & Mimura, 2016a). Importantly, these motion dependent effects originate from somewhere within the linked segment system, and the generating factors of this term can be determined and reassigned in to each of the original contributions terms from joint torques and gravitational forces (Koike & Harada, 2014; Koike & Mimura, 2016b).
We aimed to determine the dynamic contributions to kicking foot speed in rugby place kicking. The contributions of the joint torque term, motion dependent term and gravitational term were firstly determined. The generating factors of the motion dependent term were then calculated to identify which joint torques contribute most to the speed of the kicking foot centre of gravity.

METHODS: Three Japanese male rugby players (height: 1.74 ± 0.02 m, mass: 80.7 ± 3.1 kg) performed a series of 5 - 8 place kicks in a large indoor volume. The ball was placed on a tee of their preference and kicked in to a net approximately 5 m in front of the tee. The kickers were instructed to kick as far and as straight as possible and the kick with the highest subjective rating from the kicker was selected for analysis. Kinematic data (47 markers on the body; 6 markers on the ball) were captured with a motion capture system (VICON-MX; 14-camera; 250 Hz). Kinetic data under the support leg was measured with a force platform (9287, Kistler Inst.; 1000Hz). The kicking action was divided into two phases: flight and support. These were the period from the final take-off of the kicking foot to touchdown of support foot, and the period from support foot touchdown to ball impact. All data were time-normalised to the duration of these phases as -200 to -100% and -100% to 0%.

The whole body was modelled as a system of 15 rigid-linked segments. A virtual torso joint was assumed to be located between upper and lower trunk segments. The support foot was assumed to be connected with the ground via a virtual joint at the center of pressure (COP) of the foot (Koike et al., 2007). Anatomical constraint axes (e.g. varus/valgus axis at elbow and knee joints; internal/external rotation axis at wrist and ankle joints) were also considered in the modelling (Koike & Harada, 2014).

With use of a generalized velocity vector, $\boldsymbol{V}$, which consists of linear and angular velocity vectors of all the segments, the equation of motion for whole body was written as:

$$\dot{\boldsymbol{V}} = \text{(joint torque term)} + \text{(gravitational term)} + \text{(motion-dependent term)} + \text{(modeling error term)} \tag{1}$$

where $\dot{\boldsymbol{V}}$ denotes the generalized acceleration vector, which is the time derivative of the generalized velocity vector. This equation shows the contribution of the individual terms, namely the joint torque term, gravitational term, motion-dependent term (MDT) and the modelling error term (Koike & Mimura, 2016a), to the generation of the generalized acceleration vector. The MDT can be expressed as the product of the coefficient matrix $\bar{\boldsymbol{A}}_V$ and the generalized velocity vector as:

$$\text{MDT} = \bar{\boldsymbol{A}}_V \boldsymbol{V} \tag{2}$$

Assuming that the vector $\boldsymbol{\Lambda}_V$ is the sum of the following terms:

$$\boldsymbol{\Lambda}_V = \text{(joint torque term)} + \text{(gravitational term)} + \text{(modeling error term)} \tag{3}$$

the equation of motion for the whole body is expressed by the following:

$$\dot{\boldsymbol{V}}(k) = \boldsymbol{\Lambda}_V(k) + \bar{\boldsymbol{A}}_V(k)\boldsymbol{V}(k) \tag{4}$$

The generalized acceleration vector can be expressed by a difference approximation using the time interval Δt of the discretized system shown by the following equation:

$$\dot{\boldsymbol{V}}(k) = \frac{\boldsymbol{V}(k+1) - \boldsymbol{V}(k)}{\Delta t} \tag{5}$$

Substituting eq.(5) into eq.(4) yields a recurrence formula with respect to the generalized velocity vector as follows (Koike & Harada, 2014):

$$\boldsymbol{V}(k+1) = \Delta t \boldsymbol{\Lambda}_V(k) + \boldsymbol{\Psi}_V(k)\boldsymbol{V}(k), \quad \boldsymbol{\Psi}_V(k) = \boldsymbol{E} + \Delta t \bar{\boldsymbol{A}}_V(k) \tag{6}$$

Equations (3) and (6) provide the information about the contributions of the input terms $\boldsymbol{\Lambda}_V$ (i.e. the joint torque term, gravitational term, and modeling error term) at time *k*, to the generation of the generalized velocity vector at time *k*+1 in the discrete-time system.

By using eq.(6), the contribution of the time history of $\boldsymbol{\Lambda}_V$, expressed by eq.(3), to the generation of the generalized velocity vector at time k, can be quantified as shown below:

$$\boldsymbol{V}(k) = \Delta t \sum_{h=1}^{k-1} \left[\left\{ \prod_{j=k-h}^{k-1} \boldsymbol{\Psi}_V(j) \right\} \boldsymbol{\Lambda}_V(h-1) \right] + \left\{ \prod_{j=0}^{k-1} \boldsymbol{\Psi}_V(j) \right\} \boldsymbol{V}(0) \tag{7}$$

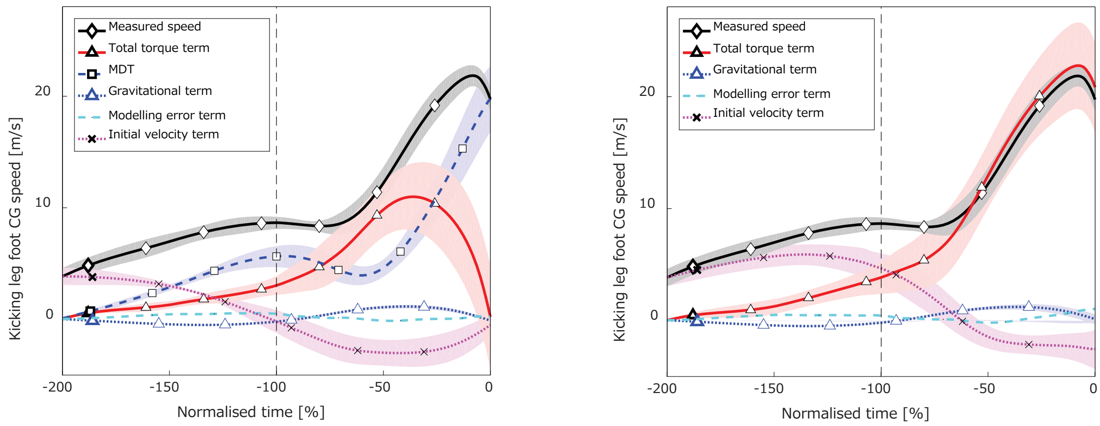
where the function Π denotes the factorial function. This equation shows the cumulative effect of the inputs to the generation of the generalized velocity vector at time *k*.

By extracting the linear and angular velocity vectors of the foot segment from the generalized velocity vector for calculating the speed of kicking leg foot's centre of gravity (CG), the time-history contributions of the individual terms to the generation of the foot speed at ball impact can be obtained as follows:

$$S_{\text{foot,CG}}(k_{\text{impact}}) = C_{\text{Trq}} + C_{\text{gravity}} + C_{\text{err}} + C_{v0} \tag{8}$$

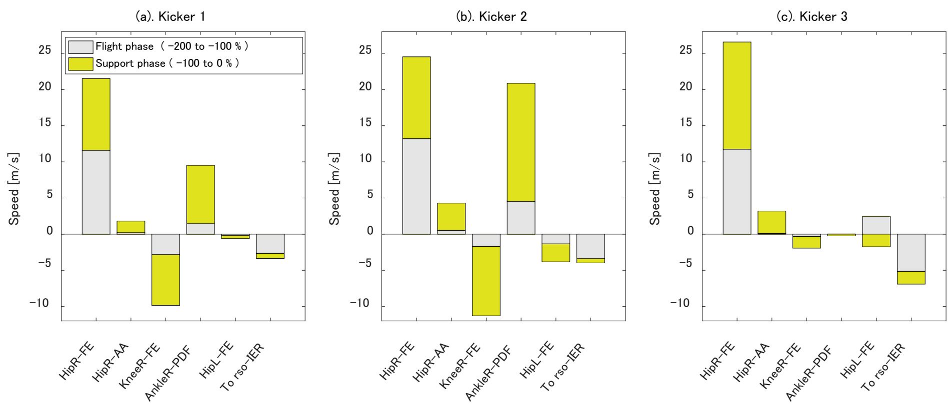
where $S_{\text{foot,CG}}(k_{\text{impact}})$ denotes the speed of the foot CG at the ball impact, and C_{Trq}, C_{gravity}, C_{err} and C_{v0} denote the time-history contributions of the joint torque term, the gravitational term, the modeling error term and the initial velocity term, respectively. Furthermore, the contribution of the joint torque term can be decomposed into the contributions of the individual joint torque terms (Koike & Harada, 2014).

RESULTS AND DISCUSSION: Figure 1(a) shows the mean ± SD contributions of the individual terms to the generation of the kicking leg foot CG speed during the kicking motion. The joint torque term contribution increased gradually from -200% to -40% normalised time and then decreased towards ball impact (0% time). The contribution of the MDT increased gradually toward -100% (support foot contact), then decreased until -60% before increasing considerably and reaching its peak at ball impact. Figure 1(b) shows the contributions of the individual terms with consideration of the generating factors of the MDT. Comparing figures 1(a) and 1(b), it is clear that the main generating factor of the MDT is the joint torque term. The initial velocity term contributed largely to the kicking leg foot CG speed during the flight phase (-200% to -100%), whereas the joint torque term was the largest contributor to kicking foot CG speed during the support phase. The contributions of the gravitational term and the modelling error terms remained small over the duration of the movement.



(a) Without conversion of the MDT (b) With conversion of the MDT into other terms

Figure 1: Mean and SD (n=3 kickers) time-histories of the contributions of the individual terms to the kicking leg foot CG speed.



R: right side (kicking leg side)
L: left side (support leg side)

FE: flexion/extension
AA: adduction/abduction
PDF: plantar/dorsal -flexion
IER: internal/external -rotation

Figure 2: Main contributors to the kicking foot CG speed after consideration of the generating factors of the MDT.

Figure 2 shows the individual differences in the main contributors to the generation of the kicking foot CG speed at ball impact between the three kickers. The contributions are divided into those generated during the flight phase (-200 to -100 %; grey) and those during the support phase (-100 to 0 %; yellow). The flexion/extension (FE) axial torque at the kicking leg hip joint contributes largely to the foot speed for all kickers in both phases. The FE axial torque at the kicking leg knee joint typically contributes to the braking of the foot speed - this contribution was observed for kickers 1 and 2, but was minimal for kicker 3. The plantar/dorsal flexion (PDF) torque at the kicking leg ankle joint shows a large contribution during the support phase for kickers 1 and 2, but not for kicker 3.

CONCLUSION: This study has determined the dynamic contributions to the generation of kicking foot speed during rugby place kicking. The motion-dependent term shows the largest contribution to kicking foot speed. This originates from the joint torque term, of which the kicking hip flexion torque consistently shows the largest positive contribution for all kickers. Around half of this kicking hip flexor contribution occurs during the flight phase. An early hip flexor action may therefore be important for utilising motion-dependent effects to obtain a large kicking foot speed at ball impact. However the hip is in its most extended position during flight and coaches should therefore consider potential injury risk implications. The kicking knee flexion torque contributes negatively to foot speed, and this may also be of interest to coaches from an injury risk perspective, especially given the difference in magnitude of this contribution between the kickers. Kickers 1 and 2 also exhibited a large positive contribution from the ankle dorsiflexor torque. Although the magnitude of this actual torque is relatively small, it may play an important role for performance by facilitating a greater effective foot mass at impact and coaches should be encouraged to explore strategies which encourage dorsiflexor action during the downswing. This understanding of the dynamic contributions to rugby place kicking provides a theoretical basis upon which coaching interventions to enhance performance or reduce injury risk could be developed.

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