Book chapter :
Bezodis, N., Atack, A. & Winter, S. (n.d). *The biomechanics of place kicking in Rugby Union.* Hiroyuki Nunome, Ewald Hennig, Neal Smith (Ed.), Football Biomechanics, London: Routledge.

The biomechanics of place kicking in Rugby Union

Neil Bezodis, Alexandra Atack and Stacy Winter

1. INTRODUCTION

Place kicks provide a means through which to score points in Rugby Union. They are a prevalent feature of the modern game with 45% of the total points scored in 582 international matches over a recent 10 year period coming from place kicks (Quarrie & Hopkins, 2015). The outcome of a single place kick can also be the determining factor in the outcome of an entire match; in the sample of matches analysed by Quarrie & Hopkins (2015), 33 match results depended directly on the success of a place kick. Additionally, the result of 14% of all of the matches would have differed if the place kick success percentages of the two teams were reversed. In spite of this clear importance of place kicking in Rugby Union, biomechanical research into rugby place kicking remains relatively scarce in comparison to that undertaken in other football codes, in particular instep kicking in soccer. However, as the average success rate for the 6,428 place kicks analysed by Quarrie & Hopkins (2015) was 73%, there is clear scope for rugby place kicking technique research to support improvements in performance levels and ultimately to affect the outcome of matches.

Given the applied nature of the challenge of improving rugby place kicking performance, it is important that any research undertaken leads to outcomes of improved practice of coaches and kickers. The approach adopted in this chapter is therefore based around Bishop's (2008) Applied Research Model for the Sport Sciences (ARMSS), which aims to “guide the direction of research required to build our evidence base about how to improve performance” (Bishop, 2008, p. 253). The ARMSS model provides a useful framework around which to seek enhanced understanding of, and subsequently the coaching and execution of, rugby place kick technique. Owing to the relative lack of existing research in rugby place kicking, it is imperative that the ARMSS model is addressed from its first stage. This stage involves the identification of real-world issues faced by coaches and athletes and requires consideration of any relevant existing literature to determine the current state of the knowledge. Early discussions between researchers and coaches are important for the success of such applied research, particularly at this early stage (Bishop, 2008). This will yield a more holistic and applied understanding and it is therefore more likely that potential problems can be clearly defined, allowing relevant research questions that will contribute to performance to be formulated. The second stage of the ARMSS, which helps to move research questions forward from this initial understanding, is based on descriptive research. Access to descriptive data from high-level place kickers can be used to provide valuable insight to inform and direct future research which will extend the evidence base further and ultimately lead to performance improvements.

The aim of this chapter is therefore to integrate experiential knowledge from an expert coach with existing biomechanical evidence and empirical kinematic data from high-level performers to develop the current understanding of technical aspects of rugby place kicking. This integration of qualitative and quantitative data from high-level applied practice is intended to provide relevant preliminary evidence upon which future experiments, applied interventions, and coaching practice can be based. It is hoped that the findings presented in this chapter will stimulate future interest in specific aspects of the biomechanics of rugby place kicking, which will further develop the understanding and, most importantly, will improve performance.

2. METHODS

2.1 Participants

Following institutional ethical approval, one male International Performance Coach (age: 47 years) and 14 male place kickers (mean ± SD age: 19 ± 1 years; mass: 87.2 ± 7.6 kg; height: 1.83 ± 0.05 m) provided written informed consent to participate. The coach held the highest-level Rugby Football Union coaching qualification with a specialism in place kicking. Collectively, he had 16 years of full-time coaching experience in professional rugby, including nine years with a kicking-specific role within an International Union. The 14 place kickers were all contracted to professional Rugby Union clubs and were current International representatives at the Under 20 age group level.

2.2 Qualitative methods

An Interpretative Phenomenological Analysis (Smith, 1996) was adopted as an in-depth qualitative approach to explore the coach's understanding of place kicking. Following a pilot interview with a Rugby Football Union Level 3 qualified coach to refine the interview guide, a semi-structured interview comprising open-ended questions was conducted with the International Performance Coach at a location of his choosing. Although there was a certain element of structure to the interview, the order of questioning was dependent on the coach's responses, with freedom allowed to express his thoughts and expand on his views (Smith, 2008). The interview was transcribed verbatim and read several times by two of the authors to gain a sense of the whole before data reduction. Preliminary comments and associations were noted to develop the authors' understanding and these notes were then used to identify the emergent themes which were aligned with quotations from the transcript. During the course of analysis, the two authors had extensive discussions on the transcriptions and emerging themes to help uncover any biases in the lead author's analytic approach (Winter & Collins, 2015). Finally, member checking was performed to ensure that the representation of the coach's experiences and the emergent themes were accurate and to offer the coach the opportunity to add any further information (Brocki & Wearden, 2006).

2.3 Quantitative methods

An 11-camera motion capture system (Vicon©, MX3) was used in an indoor laboratory to obtain three-dimensional kinematic data at 240 Hz from place kicks performed by the 14 participants. Data were collected over a two and a half year period and all kickers were current members of the Under 20 International squad at the time they were analysed. All kickers wore their own moulded rubber boots and, following a self-directed warm-up, performed a series of place kicks using a size 5 Gilbert Virtuo match ball from a kicking tee of their preference. All kicks were of maximal effort into a net which was placed approximately 2 m in front of the tee. Kickers were asked to aim towards a vertical line suspended in the net which represented the centre of the goalposts. The global Y-axis was defined horizontally along a line from the centre of the ball to the centre of the vertical target line, the Z-axis was vertical and the X-axis was determined as the cross-product of the Y- and Z-axes. The tee and net were located in a position which ensured that the non-kicking foot landed near the centre of a force platform (Kistler, 9287BA, 960 Hz) which was covered and flush with the surrounding rubber floor. Eighty reflective markers were placed on the kicker at specific anatomical locations to define a 14 segment rigid body model using a CAST approach (Cappozzo *et al*., 1995) and 54 of these markers were retained to track the segmental kinematics during each kick (Figure 1). Six markers were also placed on the ball to enable determination of the ball centre of mass (CM). Marker trajectories were labelled using Nexus (v. 1.8, Vicon©) and data were then exported for processing and analysis in Visual3D™ (v. 5.02, C-Motion, Inc.).

**** FIGURE 3.1 NEAR HERE****

Resultant ball velocity was determined from the first derivative of polynomial functions fitted through the first five frames of raw ball CM displacement data after ball contact. Raw data from all of the markers attached to the kickers were low-pass filtered at 18 Hz. The segmental kinematics were then reconstructed from these filtered marker trajectories using an evenly-weighted inverse kinematics approach (Lu & O'Connor, 1999) and segmental and joint angles were calculated using an XYZ Cardan rotation sequence. Segmental inertia data were obtained from de Leva (1996) and whole body CM location was determined using a summation of segmental moments approach. Support foot contact was identified where the vertical ground reaction force first exceeded 10 N. Specific discrete kinematic variables (Figure 2) that were deemed to relate to the coach's interview responses were then extracted and the mean values for each kicker across four kicks were calculated. For all variables of interest, the 14 data values (i.e. one from each kicker) were checked for normality ($p > 0.05$) using a Shapiro-Wilk test and the mean and standard deviation (SD) of the group-wide data were calculated. Maximum and minimum values from the group-wide data were also extracted to illustrate the extremes in the identified features of technique across this group of kickers of relatively homogeneous ability level.

**** FIGURE 3.2 NEAR HERE****

3. RESULTS AND DISCUSSION

The interview lasted 57 minutes and the subsequent analysis of the coach's understanding revealed two emergent themes of relevance to the aims of this chapter. The first theme corresponded to the general aims and philosophy of the coach who made it clear that, "*the be all and end all in this profession is results*". However, in addition to kicking success percentages - "*anything above 80% is good*" - it was also important for the coach to consider "*the longevity of the player…he could kick eight out of eight one week and then not play for the next ten weeks; that defeats the object*". Given the average success rate of 73% reported by Quarrie & Hopkins (2015), the achievement of 80% appears to be a suitable goal which sports biomechanists, working closely with coaches, clearly have the potential to support. Previous rugby place kicking research has focussed entirely on performance outcome, typically in terms of ball velocity, but it is clear from the coach's response that injury prevention is also a necessary consideration. The technical attributes subsequently identified by the coach should therefore be considered in the context of player welfare in addition to performance outcome, and future research should be clear about its focus whilst remaining mindful of this dual consideration.

The second emergent theme corresponded to the attributes associated with successful place kicking and was subdivided in to technical, mental, and physical factors. Given the aim of this chapter, the technical attributes were explored in detail during the interview. A phase analysis (Lees, 2002) was applied to retrospectively divide these technical attributes in to different phases of the movement, namely the approach (all actions up to and including support foot contact), the kicking action (from support foot contact to ball contact), and the follow through (from ball contact onwards). The technical attributes which the coach identified within these phases were then used to guide the variables extracted (Table 3.1) from the quantitative analysis of the 14 high-level kickers. The ability level of these kickers was reinforced by the resultant ball velocities they achieved during the laboratory analysis (mean ± SD = 27.4 ± 1.9 m/s, range = 24.5 to 30.5 m/s). These values are higher than those previously reported from a group of professional kickers (n = 14, mean ± SD = 26.4 ± 3.0 m/s; Holmes *et al*., 2006) and from groups of lower-level kickers (mean values ranging from 17.8 to 26.4 m/s; Baktash *et al*., 2009; Bezodis *et al*., 2007; Padulo *et al*., 2013; Sinclair *et al*., 2014; Zhang *et al*., 2012).

**** TABLE 3.1 NEAR HERE****

Ball angle: The angle of the long axis of the ball about the global medio-lateral (X) axis (see Figure 2a). 0˚ represents a vertically aligned long axis of the ball, positive angles represent the top of the ball anterior to the bottom of the ball. Approach angle: The direction of whole body CM motion in the horizontal (X-Y) plane during the airborne phase immediately prior to support foot contact (see Figure 2b). 0˚ represents motion directly along the line towards the target (i.e. Y-axis), positive angles represent approaching from towards the non-kicking leg side. Antero-posterior distance between support foot CM and ball CM: A negative value represents the foot CM ahead of the ball CM. Pelvis angle: The angle of the pelvis about the global vertical (Z) axis (see Figure 2e). 90˚ represents the line between both ASIS being perpendicular to the line of the target (i.e. Y-axis), angles >90˚ represent the kicking side of the pelvis retracted further away from the target than the non-kicking side. Thigh angle: The angle of the thigh segment about the global medio-lateral (X) axis (see Figure 2f). 0˚ represents a vertically oriented thigh segment, positive values represent the distal end of thigh rotated anteriorly relative to the proximal end. *The median value is presented because the Shapiro-Wilk test revealed data to not be normally distributed (note: all kickers exhibited values between -52˚ and -71˚, aside from one kicker who had a value of -24˚). Foot angle: The angle of the foot segment about the global medio-lateral (X) axis (see Figure 2j). 0˚ represents a vertically oriented foot segment, positive values represent the distal end of the foot rotated anteriorly relative to the proximal end. Kicking leg ankle angle at ball contact: Relative angle between the foot and shank segment (see Figure 2k), positive values represent plantar flexion relative to the angle in the static trial.

3.1 The approach

The coach identified that ball placement on the tee is largely individual, stating: "*there's an advance for people leaning the ball slightly to open a sweet spot…some like [to kick] on the point…others [prefer to position the ball] upright*". The quantitative data confirmed this as the orientation of the long axis of the ball on the tee about the global medio-lateral (X) axis ranged from 2˚ (near vertical) to 56˚ (top of the ball pointing towards the posts) between kickers (Figure 2a). Further analysis of the data revealed that five of the kickers positioned the ball between 53˚ and 56˚ ('kicking on the point'), whilst eight positioned the ball between 2˚ and 26˚ ('leaning the ball slightly') and only one of the 14 kickers used a ball angle (34˚) between these two distinct set ups. Given that a rugby ball is not spherical, it is likely that these different orientations affect the foot-ball interaction at contact. Future high-speed analysis of this foot-ball interaction, similar to that previously performed for soccer kicking (e.g., Ishii *et al*., 2012), could yield valuable insight regarding the relative merits of different ball orientations and their potential interactions with the rugby place kicking techniques used.

All kickers adopted an angled approach towards the ball; the direction of CM displacement in the horizontal X-Y plane during the final airborne phase immediately prior to support foot contact ranged from 25˚ to 47˚ relative to the Y-axis (mean ± SD = 34 ± 6˚; Figure 2b). While not explicitly discussed by the coach, this angled approach may serve to facilitate some of the specific technical features he subsequently identified as important, such as pelvic retraction on the kicking leg side at support foot contact (Figure 2e). Although experimental manipulations to approach angle were previously investigated in rugby place kicking by Padulo *et al*. (2013), only kicking knee angular kinematics were reported and no effects of different approach angles were found on these. The use of an angled approach by the kickers in the current investigation is consistent with that commonly observed in soccer instep kicking, where it has been proposed to influence pelvis kinematics at support foot contact (Lees *et al*., 2010). The direction of the approach in rugby place kicking could therefore influence pelvis or upper body kinematics at support foot contact and this is an area worthy of future investigation, particularly given the coach's comments on the importance of body configuration at support foot contact which are addressed in the *kicking action* section of this discussion.

Upon landing from the final airborne phase, the support foot CM was placed just over 0.3 m from the ball CM in the global medio-lateral (X-axis, Figure 2c) direction. This was relatively consistent between kickers (mean ± SD = 0.32 ± 0.04 m) and the mean value matches the mean medio-lateral distance previously reported between the heel and ball from a separate group of 15 professional place kickers (Cockcroft & van den Heever, 2016). There was slightly more variation in the antero-posterior (Y-axis) foot placement (mean ± SD = 0.09 ± 0.07 m, Figure 2d); most kickers positioned their support foot CM behind the ball CM (up to a maximum of 0.19 m) although one kicker placed it directly in line and another placed the foot 0.02 m ahead of the ball CM. Support foot placement has previously been shown to be consistent both within and between kickers, particularly when compared with foot placement in the two prior approach steps (Cockcroft & van den Heever, 2016). This relatively low inter- and intra-kicker variation in support foot placement suggests that previous experimental manipulations of 0.30 m in anterior, posterior, and medial directions in rugby place kicking (Baktash al., 2009) may have been excessive and therefore of limited ecological validity. However, given that the support foot is the most distal segment of the linked-segment kicker system and that it locates the kicker in the global space relative to the location of the ball, its placement likely plays an important role in dictating the path of the kicking foot. As the coach subsequently attributed importance to the path of the kicking foot when discussing the kicking action, support foot placement should remain an important consideration when investigating rugby place kicking technique.

3.2 The kicking action (from support foot contact to ball contact)

The coach discussed the importance of a "*triangle*" between the support foot, the kicking foot and the non-kicking side shoulder at support foot contact. He suggested that, "*the more stretched this is, the more power that should hopefully be generated*". The "*stretch*" of the non-kicking side shoulder and kicking foot away from the support foot at contact could relate to a 'tension arc' which was previously identified in skilled soccer players performing instep kicks (Shan & Westerhoff, 2005). Shan and Westerhoff (2005) proposed that increased length of trunk and hip flexor musculature at support foot contact assisted the subsequent generation of larger concentric muscle forces, supporting the coach's suggestion that the "*triangle [is] like an elastic band, stretch it*". The current cohort of kickers landed with their pelvis retracted away from the posts on the kicking side at support foot contact (by 139 ± 9˚ relative to the pelvis being parallel to the Y-axis, Figure 2e), a feature of technique which was likely enabled by the angled approach discussed previously. Hip extension was evident around support foot contact, serving to rotate the thigh segment away from the ball (mean ± SD absolute thigh angle about the global medio-lateral (X) axis = -56 ± 10˚, Figure 2f). This combination of pelvic retraction and hip extension therefore facilitated the "*stretch*" between the two feet in the "*triangle*" at support foot contact.

While the "*stretch*" of the non-kicking side shoulder from the feet could directly relate to the creation of a 'tension arc' (Shan & Westerhoff, 2005), it may also be an effect of movements of the non-kicking side arm. At support foot contact, the non-kicking-side arm was abducted and horizontally extended such that the wrist was 0.97 ± 0.09 m (53 ± 5% of total standing height) away from the pelvis (Figure 2g). This is a position from which non-kicking side arm can generate considerable angular momentum during the kicking phase, a feature which has previously been identified as important for accurate rugby place kicking, particularly when also striving to achieve maximal distance (Bezodis *et al*., 2007). The third point of the coach's "*triangle*", the non-kicking foot, was "*stretched*" away from other parts of the body through a relatively extended knee (27 ± 5˚ of flexion, Figure 2h) at support foot contact. The coach used the analogy of a rigid "*pillar*" for the non-kicking leg and suggested the importance of "*locking out your [non-kicking] leg in order for your [kicking leg] to strike through*". However, all kickers exhibited further support leg knee flexion (mean ± SD total range of flexion = 22 ± 4˚) between support foot contact and ball contact. While completely eliminating knee flexion during the kicking action (i.e. maintaining a rigid "*pillar*") therefore appears to be an unlikely expectation based on the amount of flexion exhibited by these high-level kickers, it is plausible that limiting the amount of flexion could be an important feature of place kicking technique. Future research should therefore consider the importance of the support leg and assess the relative merits of technical or physical coaching methods designed to limit support leg knee flexion during place kicking.

From the "*stretched*" position at support foot contact, the coach made it clear that, "*the hip leads the knee, the knee then snaps the shank that snaps the foot through the ball underneath it*". Such proximal-to-distal sequencing is a widely accepted feature of striking skills such as kicking (Putnam, 1993). All of the analysed kickers exhibited clear proximal-to-distal sequencing in the linear velocities of the segment endpoints (i.e., hip, knee, ankle) and the segmental angular velocities (i.e., thigh, shank), confirming the existence of this sequencing in high-level rugby place kickers. In addition to this, the coach suggested that kickers could not be successful "*if they haven't got any…coordination*". Although it is beyond the scope of the preliminary descriptive nature of this chapter, intra-limb coordination remains relatively unexplored in kicking actions but may be a relevant direction for future research, particularly if the research questions are concerned with the learning and development of rugby place kicking technique (Chow *et al*., 2007; 2008).

The coach proposed that the kicking foot should travel "*in a straight line going through…towards the target…from six to twelve inches behind the ball [until]…six to twelve inches after impact*". However, closer inspection of the raw trajectories of the kicking foot CM from the empirical data (Figure 2i) appeared to partly conflict this. Over the 0.3 m antero-posterior distance immediately behind the point of ball contact, the foot CM travelled in a curvilinear path, and the kickers exhibited a medio-lateral range of foot CM motion of 0.11 ± 0.02 m. This appears logical given the linked-segment nature of the system and that the path of the foot has been shown to follow an inclined plane during soccer kicking (Alcock *et al*., 2012). However, in the 0.3 m immediately after the point of ball contact, the medio-lateral range of motion of the foot CM was considerably less (mean ± SD = 0.02 ± 0.01 m). This suggests that although the foot may not be travelling in a straight line towards the target immediately prior to ball contact, during the actual volume where ball contact is made, the foot path is near straight towards the target. Given the relatively homogeneous and high ability level of the studied kickers, this may be a feature of their skill level, particularly as this is likely to affect consistent, accurate kicking. Further investigation prior to, during and after ball contact is required to fully understand the importance of the path of the kicking foot. This could also assess the appropriateness and potential influence of the "*foot towards target*" principle, which was held by the coach and is a technical feature proposed to be important across several coaching texts (e.g., Biscombe & Drewett, 1998; Greenwood, 2003; Wilkinson, 2005). The coach also suggested that at ball contact, the foot should be "*toe down…promote the hard part of the foot striking through the ball*". This appears logical given the nature of impact mechanics and the desired outcome of a high ball velocity. The kicking foot segment of the kickers was angled at 46 ± 8˚ relative to the global medio-lateral (X) axis at ball contact (Figure 2j), and this was partly achieved through 25 ± 6˚ more plantar flexion than in a neutral standing position (Figure 2k). Given the previously identified variation in ball angle on the kicking tee, it would be prudent to investigate potential interactions between these foot kinematics and the initial ball angle, and this should be done using high-speed video given the relatively short duration of foot-ball contact.

3.3 The follow through

The coach suggested that the follow through is important because "*there needs to be a…release mechanism…at the end…to dissipate the energy build up [due to] the forces they're putting on themselves*". He also identified that the follow through is typically highly individual and that it may be "*a hop or a skip, it may be a run, a step on your kicking foot afterwards. It may be whatever it is but there needs to be a release*". Simple visual analysis of the 14 kickers confirmed that different strategies existed as nine kickers 'hopped' forwards to land on their non-kicking leg in the next ground contact after ball contact, while the remaining five kickers 'stepped' forward to take the next ground contact phase with their kicking leg. The kickers with the 'hopping' style exhibited peak kicking hip flexion ranging from 100 to 121˚ during the follow through, with the foot CM reaching a peak height of 42 to 62% of standing height (Figure 2l). In contrast, the kickers with the 'stepping' style follow through exhibited less peak kicking hip flexion (range = 88 to 93˚) and a lower peak foot CM height (range = 28 to 38%). Given that the ball has left the foot, and thus the performance outcome of the movement has been determined by the time of the follow through, it has seldom been analysed in previous rugby kicking research which has all been performance outcome focussed. However, player longevity is also an important outcome consideration, particularly given the previously discussed comments in relation to the coach's aims and philosophy. The demands of the follow through on the musculo-skeletal system are therefore of interest for future research, particularly given the different follow through strategies evident within this relatively homogenous-ability level group of kickers. Interestingly, it was recently demonstrated that experimental manipulations to the follow through could be useful when learning variations of simple motor skills such as grasping the handle of a robotic interface (Howard *et al*., 2015). If these findings transfer to whole body skills such as kicking, follow through manipulations could be used in performance outcome focussed research in an attempt to experimentally affect movements during the kicking action phase.

4. CONCLUSION

The qualitative data obtained from the semi-structured interview with the coach yielded a rich, experiential understanding of rugby place kicking technique. These data were used to identify potentially important features of rugby place kicking technique during the approach, the kicking action and the follow through. Three-dimensional kinematic data were then used to quantify these features of technique amongst a homogeneous group of high-level place kickers. This combination of qualitative and quantitative data has highlighted several features of technique, some of which may influence others, and many of which are worthy of future applied research. Two distinct styles of ball placement on the tee were identified and these may influence, or be influenced by, the foot kinematics at ball contact. The angle at which a kicker approaches the ball may also be of interest for understanding how it influences pelvis kinematics at support foot contact, and ultimately how the kicking leg segments are consequently affected. The location of support foot contact is also a potentially related consideration as it affects the location of these other segments, all of which combine to determine the path of the kicking foot before, during and after ball contact. Different styles in the follow through used after ball contact were also identified and the implications of these for both injury and performance should be investigated.

Clearly the biomechanical understanding of rugby place kicking remains in its relative infancy. This chapter aimed to provide an appropriate, evidence-based overview of some of the important features of technique and it is hoped that it will stimulate future experimental and theoretical biomechanical research to further the current understanding and ultimately to improve rugby place kicking performance.

ACKNOWLEDGEMENTS

The authors are grateful to Mr Jack Lineham for his technical assistance throughout

the quantitative data collection.

REFERENCES

Alcock, A. M., Gilleard, W., Hunter, A. B., Baker, J., and Brown, N. (2012). Curve and instep kinematics in elite female footballers. *Journal of Sports Sciences*, *30*(4), 387–394.

Baktash, S., Hy, A., Muir, S., Walton, T., and Zhang, Y. (2009). The effects of different instep foot positions on ball velocity in place kicking. *International Journal of Sports Science and Engineering*, *3*(2), 85–92.

Bezodis, N., Trewartha, G., Wilson, C., and Irwin, G. (2007). Contributions of the non-kicking-side arm to rugby place-kicking technique. *Sports Biomechanics*, *6*(2), 171–186.

Biscombe, T., and Drewett, P. (1998). *Rugby: Steps to success*. Champaign, IL: Human Kinetics.

Bishop, D. (2008). An applied research model for the sport sciences. *Sports Medicine*, *38*(3), 253–263.

Brocki, J. M., and Wearden, A. J. (2006). A critical evaluation of the use of interpretative phenomenological analysis (IPA) in health psychology. *Psychology and Health*, *21*(1), 87–108.

Cappozzo, A., Catani, F., Della Croce, U., and Leardini, A. (1995). Position and orientation in space of bones: anatomical frame definition and determination. *Clinical Biomechanics*, *10*(4), 171–178.

Chow, J. Y., Davids, K., Button, C., and Koh, M. (2007). Variation in coordination of a discrete multiarticular action as a function of skill level. *Journal of Motor Behavior*, *39*(6), 463–479.

Chow, J. Y., Davids, K., Button, C., and Koh, M. (2008). Coordination changes in a discrete multi-articular action as a function of practice. *Acta Psychologica*, *127*(1), 163–176.

Cockcroft, J., and van den Heever, D. (2016). A descriptive study of step alignment and foot positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports Sciences*, *34(4)*, 321–329.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov’s segment inertia parameters. *Journal of Biomechanics*, *29*(9), 1223–1230.

Greenwood, J. (2003). *Total rugby: fifteen man rugby for coach and player*. London, UK: Bloomsbury.

Howard, I. S., Wolpert, D. M., and Franklin, D. W. (2015). The value of the follow-through derives from motor learning depending on future actions. *Current Biology*, *25*(3), 397–401.

Ishii, H., Yanagiya, T., Naito, H., Katamoto, S., and Maruyama, T. (2012). Theoretical study of factors affecting ball velocity in instep soccer kicking. *Journal of Applied Biomechanics*, *28*(3), 258–270.

Lees, A. (2002). Technique analysis in sports: a critical review. *Journal of Sports Sciences*, *20*(10), 813–828.

Lees, A., Asai, T., Andersen, T. B., Nunome, H., and Sterzing, T. (2010). The biomechanics of kicking in soccer: a review. *Journal of Sports Sciences*, *28*(8), 805–817.

Lu, T.W., and O'Connor, J.J. (1999). Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *Journal of Biomechanics*, *32*(2), 129–134.

Padulo, J., Granatelli, G., Ruscello, B., and D'Ottavio, S. (2013). The place kick in rugby. *Journal of Sports Medicine and Physical Fitness*, 53(3), 224–231.

Putnam, C. A. (1993). Sequential motions of body segments in striking and throwing skills: descriptions and explanations. *Journal of Biomechanics*, *26* (Suppl. 1), 125–135.

Quarrie, K. L., and Hopkins, W. G. (2015). Evaluation of goal kicking performance in international rugby union matches. *Journal of Science and Medicine in Sport*, *18*(2), 195–198.

Shan, G., and Westerhoff, P. (2005). Full-body kinematic characteristics of the maximal instep soccer kick by male soccer players and parameters related to kick quality. *Sports Biomechanics*, *4*(1), 59–72.

Sinclair, J., Taylor, P. J., Atkins, S., Bullen, J., Smith, A., and Hobbs, S. J. (2014). The influence of lower extremity kinematics on ball release velocity during in-step place kicking in rugby union. *International Journal of Performance Analysis in Sport*, *14*(1), 64–72.

Smith, J.A. (1996). Beyond the divide between cognition and discourse: Using interpretive phenomenological analysis in health psychology. *Psychology and Health, 11*(2), 261–271.

Smith, J.A. (2008). *Qualitative psychology: A practical guide to research methods*. London, UK: Sage.

Wilkinson, J. (2005). *How to play rugby my way*. London, UK: Headline Book Publishing.

Winter, S., and Collins, D. (2015). Why do we do, what we do? *Journal of Applied Sport Psychology*, 27, 35–51.

Zhang, Y., Liu, G., and Xie, S. (2012). Movement sequences during instep rugby kick: a 3D biomechanical analysis. *International Journal of Sports Science and Engineering*, 6(2), 98–95.

Table 3.1. Selected discrete descriptive data from the group of high-level place kickers.

Variable	Mean	SD	Minimum
Ball angle on tee (°)	34	17	2
Approach angle (°)	34	6	25
Medio-lateral distance between support foot CM and ball CM (m)	0.32	0.04	0.25
Antero-posterior distance between support foot CM and ball CM (m)	0.09	0.07	-0.02
Pelvis angle at support foot contact (°)	139	9	126
Kicking leg thigh angle at support foot contact (°)	-58*	n/a	-24
Resultant distance between non-kicking-side wrist and pelvis CM at support foot contact (m)	0.97	0.09	0.84
Support leg knee flexion angle at support foot contact (°)	27	5	21
Total support leg knee flexion during support leg contact (°)	22	4	14
Medio-lateral range of motion of the kicking foot CM in the 0.3 m prior to initial ball contact (m)	0.11	0.02	0.07
Medio-lateral range of motion of the kicking foot CM in the 0.3 m after initial ball contact (m)	0.02	0.01	0.01
Kicking leg foot angle at initial ball contact (°)	46	8	32
Kicking leg ankle angle at ball contact (°)	25	6	15
Peak kicking leg hip flexion angle during follow through (°)	104	11	88
Peak height of kicking leg foot CM during follow through (% of standing height)	46	12	28

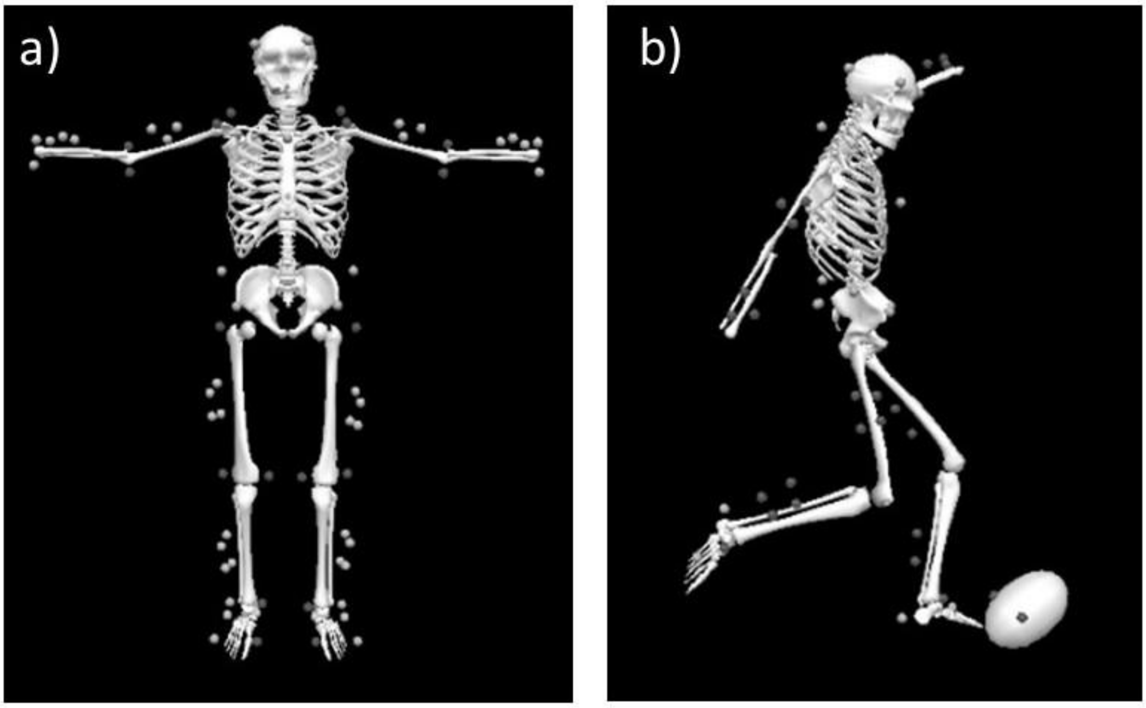

Figure 3.1. Illustration of the markers used to a) define the 14 rigid body segments in the static trial, and b) to track the segments during the dynamic kicking trials**.**

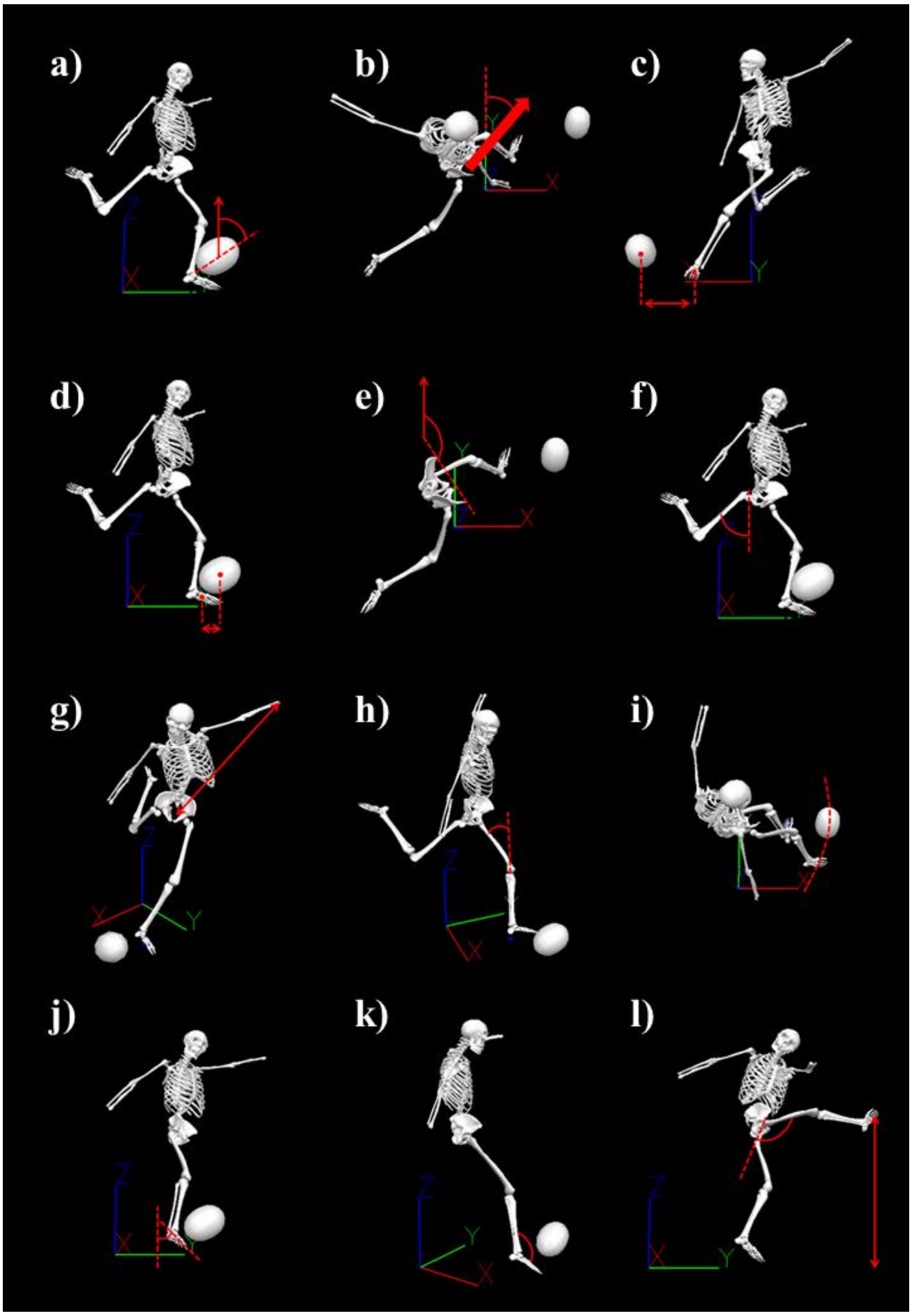

Figure 3.2. Visual identification of selected kinematic variables determined in the quantitative analysis. From left to right, top to bottom: a) ball angle; b) approach angle; c) medio-lateral support foot placement; d) antero-posterior support foot placement; e) pelvis angle at support foot contact; f) thigh angle at support foot contact; g) non-kicking-side wrist to pelvis distance at support foot contact; h) support leg knee flexion at support foot contact; i) kicking foot trajectory; j) kicking foot angle at ball contact; k) kicking leg ankle angle at ball contact; l) peak kicking leg hip flexion angle and peak kicking foot CM height during the follow through. Some segments are removed in figures e, j and k to improve the visibility of the depicted kinematic variable.