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Whole-body energy transfer strategies during football instep kicking: implications for training practices

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ABSTRACT
Knowledge of whole-body energy transfer strategies during football instep kicking can help inform empirically grounded training practices. The aim of this study was thus to investigate energy transfer strategies of 15 semi-professional players performing kicks for speed and accuracy. Three-dimensional kinematics and GRFs (both 1000 Hz) were incorporated into segment power analyses to derive energy transfers between the support leg, torso, pelvis and kick leg throughout the kick. Energy transferred from support leg ($r = 0.62$, $P = 0.013$) and torso ($r = 0.54$, $P = 0.016$) into the pelvis during tension arc formation and leg cocking was redistributed to the kick leg during the downswing ($r = 0.76$, $P < 0.001$) and were associated with faster foot velocities at ball contact. This highlights whole-body function during instep kicking. Of particular importance were: (a) regulating support leg energy absorption, (b) eccentric formation and concentric release of a 'tension arc' between the torso and kicking hip, and (c) coordinated proximal to distal sequencing of the kick leg. Resistance exercises that replicate the demands of these interactions may help develop more powerful kicking motions and varying task and/or environmental constraints might facilitate development of adaptable energy transfer strategies.

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Soccer; power; torso; pelvis; support leg

Introduction

Fast and accurate instep kicking is advantageous for a footballer as it increases the chances of scoring when shooting (Dorge et al., 2002) and helps speed up a team's movement when switching the ball to the opposite flank (Turner & Sayers, 2010). To perform a successful kick, the player swings the kick leg as an open kinetic chain so the foot: (a) reaches peak velocity at foot-to-ball contact (Lees et al., 2010; De Witt & Hinrichs, 2012), and (b) is oriented to maximise the ball's momentum in the intended direction of travel (Nunome et al., 2006). Research has shown this is achieved through coordinated application of active (i.e., neuromuscular) and passive (i.e., motion-dependent) forces to induce proximal-to-distal energy transfer through the kick leg (Dorge et al., 2002; Nunome et al., 2002, 2006; Putnam, 1991, 1993). It is well established that concentric work performed at the kicking

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Supplemental data for this article can be accessed here.

hip (i.e., flexion and adduction) adds energy to the thigh before the lower leg and foot is passively accelerated towards ball contact (Dorge et al., 2002; Lees et al., 2009; Nunome et al., 2002, 2006; Putnam, 1991; Robertson & Mosher, 1985).

However, a limitation of these findings is that they consider the kick leg independent from the rest of the body (Lees et al., 2010). More recent evidence suggests that the support leg, pelvis and torso also all contribute to kicking performance (Augustus et al., 2017; Fullenkamp et al., 2015; Inoue et al., 2014; Naito et al., 2010). Pelvis rotations about the support leg may precede kick leg sequencing (Inoue et al., 2014; Lees et al., 2009), and concentric work performed at the support knee (Augustus et al., 2017) and torso (Naito et al., 2010) may serve to extend the kicking knee later in the downswing. Unfortunately, to date, energy transfers between these segments have only been inferred indirectly. Studies have either reported energy generation/absorption at joint level only (and thus not where that energy is transferred to/from) (Augustus et al., 2017; Inoue et al., 2014; Lees et al., 2009), or inferred energy transfers from kinematic parameters (Langhout et al., 2015; Shan & Westerhoff, 2005). Given that efficient energy transmission through the kinetic chain theoretically enables faster foot velocities (Lees et al., 2010), assessment of whole-body energy transfer strategies is important for enhancing our understanding of skilled instep kicking.

Segment power analysis is one method that derives the magnitude and direction of energy transfers during human movement (Gordon et al., 1980). The technique has been used to investigate other open kinetic chain sports skills such as the tennis serve (Martin et al., 2014), table tennis backhand (Iino & Kojima, 2016) and baseball pitch (Aguinaldo & Escamilla, 2019; Howenstein et al., 2019). Collectively, these studies identified a) efficient energy transfers were associated with decreased injury risk and enhanced performance, and b) that larger (more proximal) and ground contacting segments function to transfer energy sequentially to the smaller (more distal) segments. In instep kicking, Naito et al. (2012) also highlighted the importance of redistributing energy gained during the approach to the kick leg following support foot touchdown (SFTD). However, to date, no study has comprehensively assessed whole-body energy transfers during the skill. Examination of how (i.e., muscular or passive?) and when (i.e., phases of the kick?) energy is generated, absorbed and transferred through the body can thus provide a greater depth of insight than has previously been reported. Equipped with this knowledge, coaches and practitioners will be better informed to explore strategies for developing instep kicking by focussing attention towards the features of the skill that are associated with performance. The aim of this study was therefore to: a) determine whole-body energy transfer strategies during football instep kicking, and b) use this information to help inform technical and/or strength and conditioning training practices. It was hypothesised that: a) SFTD would induce energy transfer from the support leg and pelvis into the kicking leg, b) the torso would transfer energy to the pelvis and kick leg during the downswing and c) these transfers would be positively associated with kicking foot velocities at foot-to-ball contact.

Materials and methods

Participants

Fifteen male association footballers volunteered for the study (Mean ± SD; mass 79.0 ± 7.5 kg, height 1.80 ± 0.10 m, age 23.8 ± 4.0 years). All were aged 18–35 years, affiliated to semi-professional clubs in the English FA national league (>10 years' experience), and injury free at the time of testing. Ethical approval was granted by the University's local committee and written informed consent obtained prior to data collection.

Procedures and data collection

After a self-directed warm up (~10 mins including jogging, dynamic stretches and kicks of increasing effort), participants kicked a FIFA approved size 5 football (800 Hpa; Mitre Monde, UK) with the instep of their dominant foot as 'fast and accurately' as possible towards a circular target (0.5 m radius) on a catching net 4 m from the ball in a purpose built laboratory. Inaccurate trials were discounted, and the first ten successful attempts were included for analysis (Lees & Rahnama, 2013). Approach distance was controlled to 3 m (2–5 steps) and angle to 30° as the approach which most participants self-selected for best performance.

Kinematic and ground reaction force (GRFs) data were captured at 1000 Hz using 10-camera, 3D motion analysis (T40S, Vicon, UK) and a piezoelectric force platform (9287C, Kistler, UK). Reflective markers determined the position and orientation of bilateral feet, shanks and thighs, and a pelvis, lumbar and thorax in a 6 DOF model (Figure 1; Augustus et al., 2020b). Segments were rigid geometrical volumes scaled to participant height and mass (Hanavan, 1964), inertial characteristics derived from De Leva (1996) (feet, shanks, and thighs) or Pearsall et al. (1996) (pelvis, lumbar and thorax), and the mass of the boots added to the feet (0.3 to 0.4 kg). Following static calibration, segment motion was tracked using the CAST technique (Cappozzo et al., 1995). Ankle, knee and hip joint centres were determined using functional methods (Schwartz & Rozumalski, 2005) and the lumbo-pelvic joint centre as a virtual landmark 5% along a vector between the L5-S1 marker and mid-ASIS landmark (Seay et al., 2008). These joint centres served as the origins of anatomical coordinate systems and the point of application for inverse dynamics (Figure 1). Positive Z was congruent with the long axis of the segment and pointed vertically, positive X pointed to the right, and positive Y anteriorly (Figure 1). Finally, six semi-hemispherical markers were attached to the anterior portion of the ball to define its geometric centre and enable calculation of post-strike ball velocity as described by Inoue et al. (2014).

Data processing

Marker trajectories and GRFs were exported to Visual 3D (V6, C-Motion, USA), where kicking foot and shank markers were low-pass filtered using a time-frequency, fractional Fourier filter (FrFF). The FrFF processes markers in consecutive Fourier domains to raise the cut-off frequency near the time of impact, retain high-frequency content owing to physical sources and derive valid kinematics during both swing and foot-to-ball contact (Augustus et al., 2020a, 2020b). The cut-off frequency was set as 18 Hz for the swing phase and ranged from 150 to 300 Hz for the contact phase (Augustus et al., 2020b). Ball markers were left unfiltered, but all other markers and GRFs were low-pass filtered using a conventional fourth-order, dual-pass Butterworth filter (18 Hz cut-off, determined by residual analysis) to remove erroneous peaks from support leg joint kinetics following

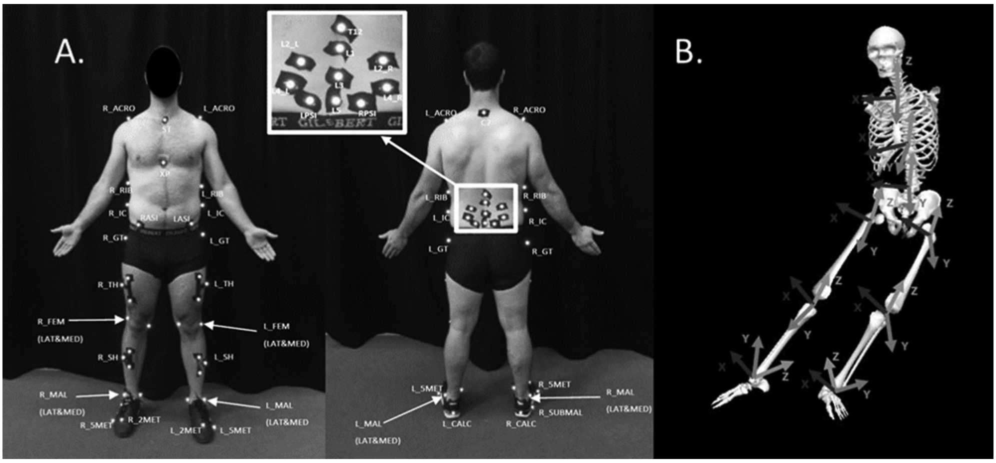

Figure 1. **A**. Marker locations and **B**. locations of joint coordinate systems at the proximal end of each segment. C = cervical spine, L = lumbar spine, T = thoracic spine, ST = sternal notch, XP = xiphoid process, ACRO = acromion, ASI = anterior superior iliac spine, PSI = posterior superior iliac spine, IC = iliac crest, GT = greater trochanter, TH = thigh, FEM = femoral epicondyle, SH = shank, MAL = malleolus, MET = metatarsal, LAT = lateral, MED = medial, SUBMAL = 5 cm inferior to malleolus. NB: L or R before or after an underscore refer to left or right side of body, and numbers to anatomical location (e.g., T12 = twelfth thoracic vertebrae).

SFTD (Bisseling & Hof, 2006). Internal joint moments and forces were estimated using Newton-Euler inverse dynamics resolved to the joint co-ordinate system (Derrick et al., 2019) and kick leg kinetic parameters reflected for the final 10 ms before ball contact to remove artefact owing to the collision between foot and ball (Augustus et al., 2020b; Nunome et al., 2006). Foot centre of mass velocity at the instance of ball contact (vector magnitude of X, Y and Z components) and post-strike ball velocity were included as measures of overall kicking performance (Inoue et al., 2014), and ball to foot velocity ratios as an indicator of foot-to-ball impact efficiency.

Segment power analyses

Processed joint moments and forces were combined with joint centre linear and segment angular velocities for the segment power analyses (Gordon et al., 1980). The rate of work done by a joint force on a segment, or Joint Power (JP), was calculated as the scalar product of joint forces (Fj) and corresponding joint centre linear velocities (vj):

$$JP = Fj \cdot vj$$

The JP represents the passive transfer of energy into (if positive) or out of (if negative) the adjoining segments across a joint. Since the joint forces are equal and opposite across a given joint, this term represents a simple exchange of energy between the adjoining segments. Further, the term 'joint power' was used here as presented by Gordon et al. (1980) and should not be confused with the description of net energy generation/absorption for a given joint rotation (i.e., product of joint moment and joint angular velocity).

The rate of work done by a joint moment on a segment, or muscle power (MP), was calculated as the scalar product of the joint moments *(Mj)* and corresponding segment angular velocities (ωs):

$$MP = Mj.\omega s$$

The MP represents energy delivered to (or removed) from segment *s* at its joint *j* due to work done by the muscles. Since the angular velocity of the two segments at a given joint may vary, there is more than a simple exchange of energy, and energy can be added or removed from the system. Positive values indicate concentric work is performed, power is generated, and energy is delivered to the segment. Negative values indicate the segment does work on the muscles, power is absorbed, and energy is removed from the segment.

Each segment therefore gains or loses energy from work done by a JP and MP at its proximal (*p*) and distal (*d*) end, and the net rate of energy input or output, or the total Segment Power (SP) is:

$$SP = JPd + JPp + MPd + MPp$$

The only exception was the pelvis, which included an extra JP and MP term for both kick and support leg hips at its distal end. While energy supplied (or removed) by the thoraco-lumbar joint was included for the lumbar segment, full data for the thorax is not reported.

When SP is integrated over a specified time interval, the result is work performed on (or by), and net energy transfer into (or out) of that segment. Similarly, the integral of the JP and MP represent energy transfers attributed to passive or active muscular contributions, respectively. Each SP, JP and MP were thus integrated using the trapezoid rule over the four phases of the kick to determine the magnitude and direction of energy transfers (Figure 2). Phase 1 'tension arc formation' occurred between kicking foot take off and SFTD (Shan & Westerhoff, 2005), phase 2 'leg cocking' between SFTD and maximal kicking knee flexion (MKF), phase 3 'early downswing' (i.e., kicking knee extension) between MKF and the instance the kicking knee extended past 90° (K90), and phase 4 'late downswing' between K90 and ball contact start (BCS).

Statistical analyses

Following normality checks, one-way repeated measures ANOVAs assessed if integrated SPs were different between the four phases of the kick. If sphericity was violated, the Greenhouse-Geisser adjustment was used and alpha was Bonferroni adjusted for multiple comparisons (number of segments = 8, $\alpha = 0.006$). Bonferroni adjusted, paired t-tests determined pairwise differences between phases (N per segment = 6, $\alpha = 0.008$), and effect sizes calculated (trivial $d < 0.2$, small $d = 0.2$–0.5, medium $d = 0.5$–0.8, large $d > 0.8$; Cohen, 1988). Pearson's correlations examined associations between energy transferred from: a) pelvis to kicking thigh between SFTD and BCS (i.e., sum of Phases 2, 3 & 4), b) the support thigh to the pelvis during the entire kick (sum of Phases 1, 2, 3 and 4) and c) the lumbar segment to pelvis during the entire kick and kicking foot velocities at BCS (0–0.2 = no correlation, 0.2–0.4 = weak, 0.4–0.7 = moderate, 0.7–1.0 = strong; Fallowfield et al., 2005). Alpha was Bonferroni adjusted to account for multiple correlations (N = 3, $\alpha = 0.05/3 = 0.017$). Statistical tests were conducted using JASP software (V0.12, University of Amsterdam, Netherlands).

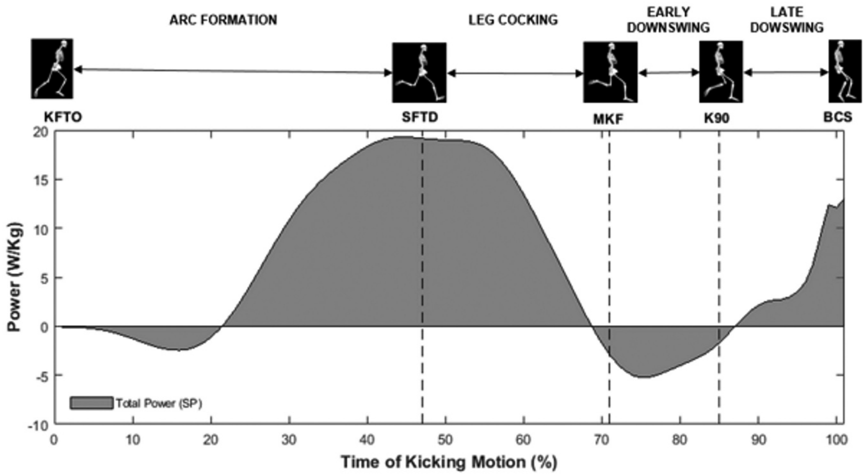

Figure 2. Representative example (kicking thigh) showing how segment power was integrated during each of the four phases of the kick to calculate contributions of energy transfer into/ out of each segment. For example, energy input (+ve) and output (-ve) of the thigh during arc formation is shown between KFTO and SFTD. The same process was used for calculating individual JP and MP terms. KFTO = kicking foot take off, SFTD = support foot touchdown, MKF = maximal kicking knee flexion, K90 = kicking knee extends past 90°, BCS = ball contact start.

Results

Foot velocities at BCS, post-strike ball velocities, and ball to foot velocity ratios were 18.6 ± 0.9 m/s, 26.3 ± 1.3 m/s and 1.4 ± 0.1, respectively. Summary energy transfer variables were all significantly correlated (moderately or strongly) with foot velocities at BCS ($P < 0.017$; Table 1 & Figure 3). Mean ± SD energy transfers per phase are shown in Figures 4 & Figure 5 and summarised in Figure 6.

Significant main effects were shown for each SP between the four phases of the kick ($P < 0.006$). Energy was transferred distal-proximally through the support leg in all phases. More energy was transferred from support foot to shank during leg cocking than other phases ($P < 0.008$; $d = 3.3–3.6$), and the support thigh lost more energy in the phases following SFTD, compared to arc formation ($P < 0.008$; $d = 1.1–2.2$). These transfers were predominated by passive JPs at the ankle, knee and hip, and MPs tended

Table 1. Pearson's correlation coefficients with 95% confidence intervals for each summary energy transfer variable with foot velocity at the instance of foot-to-ball contact.

	Pearson's Correlations (with foot velocity at ball contact)				
	r	Lower 95% CI	Upper 95% CI	R^2	p
Energy transfer from pelvis to kick thigh during downswing (J/Kg)	0.76	0.40	0.92	0.58	0.001*
Energy transfer from support thigh to pelvis during entire kick (J/Kg)	0.62	0.16	0.86	0.39	0.013*
Energy transfer from lumbar spine to pelvis during entire kick (J/kg)	0.54	0.02	0.82	0.29	0.016*

* significant correlation ($P < 0.017$)

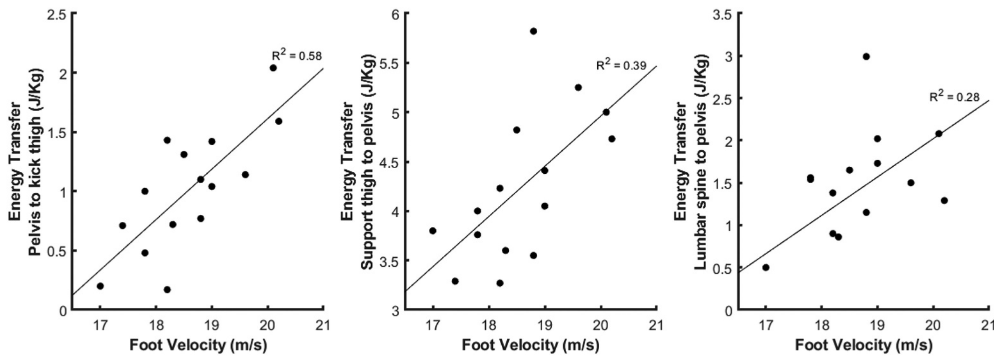

Figure 3. Relationship of each summary energy transfer variable with kicking foot velocity at the instance of foot-to-ball contact. Right: energy transfer from pelvis into kicking thigh during the downswing. Middle: from support thigh into pelvis during entire kick. Left: from lumbar segment into pelvis during the entire kick.

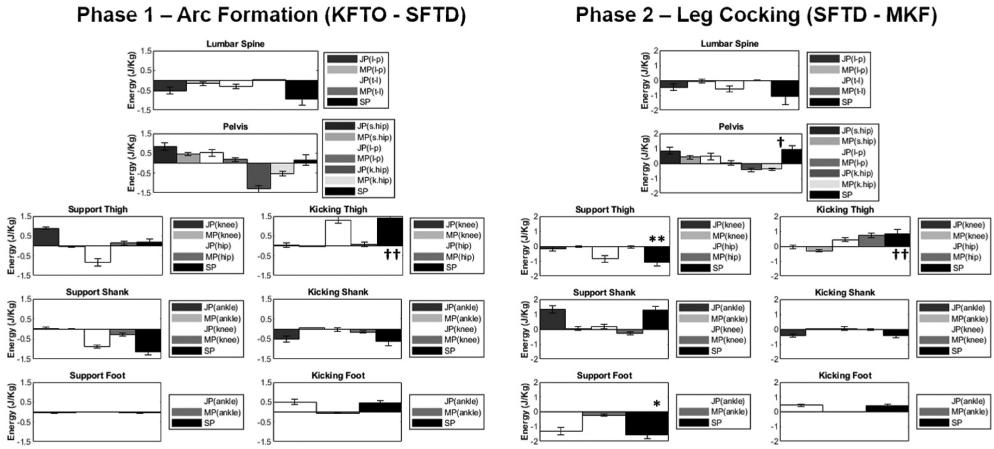

Figure 4. Mean ± SD energy transfer by joint powers (JP), muscle powers (MP) and total segment powers (SP) at each segment during arc formation (kicking foot take off (KFTO) to support foot touchdown (SFTD)) and leg cocking (SFTD to maximal kicking knee flexion (MKF)). The joint name in brackets indicates JP and MP at the proximal and distal end of each segment. NB: +ve = energy input and -ve = energy output from a segment. * = greater support foot SP than other phases. ** = greater support thigh SP than arc formation. **†** = greater pelvis SP than arc formation or late downswing. **††** = greater kicking thigh SP than early and late downswing ($P < 0.008$).

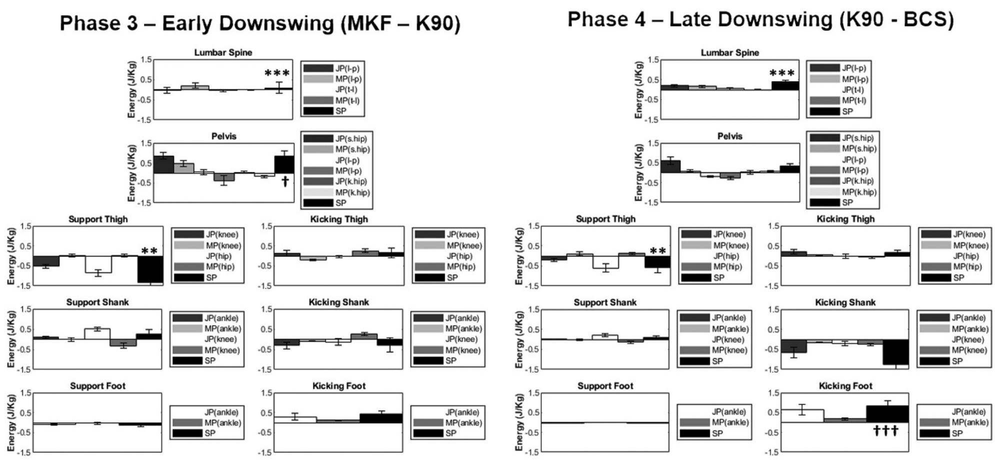

Figure 5. Mean ± SD energy transfer by joint powers (JP), muscle powers (MP) and total segment powers (SP) at each segment during early downswing (maximal kicking knee flexion (MKF) to kicking knee extension past 90° (K90)) and late downswing (K90 to ball contact start (BCS)). The joint name in brackets indicates JP and MP at the proximal and distal end of each segment. NB: +ve = energy input and -ve = energy output from a segment. ** = greater support thigh SP than arc formation. *** = greater lumbar SP than arc formation and leg cocking. **†** = greater pelvis SP than arc formation or late downswing. **†††** = greater kicking foot SP than other phases ($P < 0.008$).

to absorb energy at the knee and hip (Figures 4 & Figure 5). Of all sources of energy into the pelvis, the JP at the support hip was consistently the largest contributor. The lumbar spine also supplied energy to the pelvis early in the kick (i.e., during tensions arc

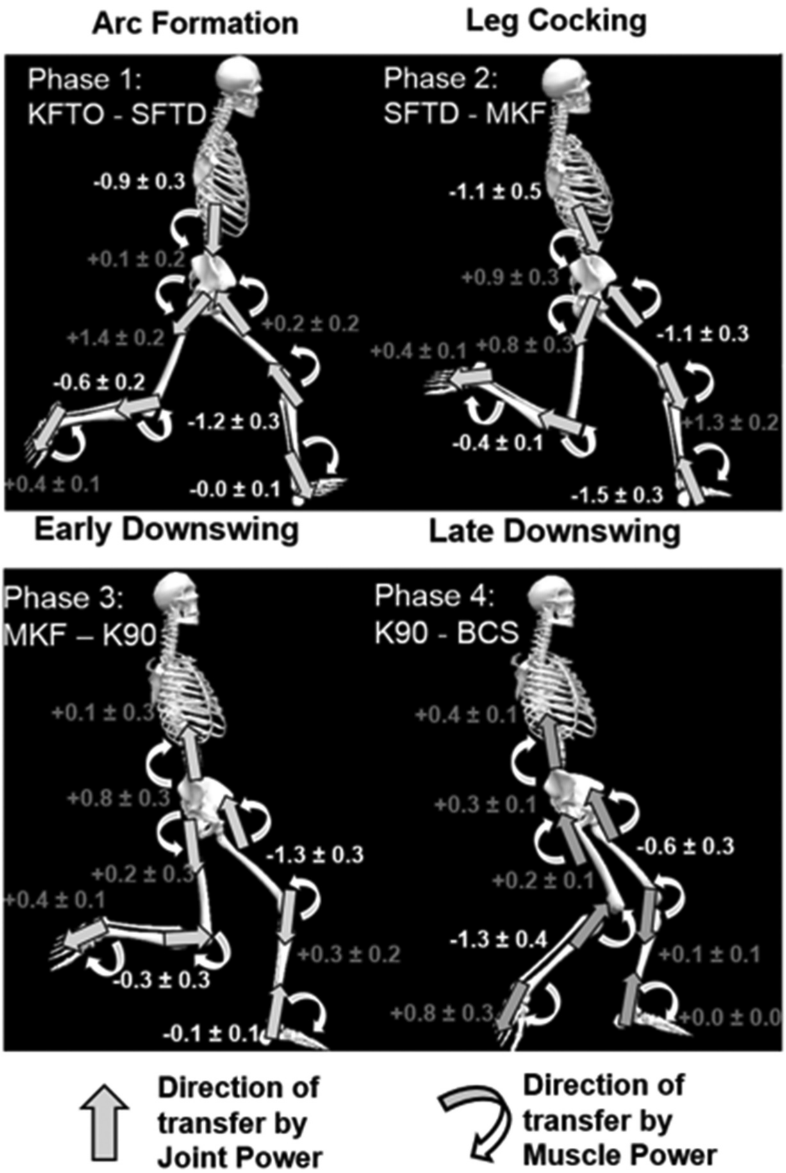

Figure 6. Summary of mean ± SD total energy input or output (SP; J/Kg) to (if +ve) or from (if -ve) each segment during the four phases of the kick. Straight arrows show the direction of energy transfer by joint power, and curved arrows show the direction of energy transfer by the muscle power at each joint. KFTO = kicking foot take off, SFTD = support foot touchdown, MKF = maximal kicking knee flexion, K90 = knee extension > 90°, BCS = ball contact start, JP = joint power, MP = muscle power.

formation and leg cocking) before transfers reversed during the downswing phases (Figures 4 & Figure 5; P < 0.008; d = 1.3–1.9). In total, more energy was thus added to the pelvis following SFTD (i.e., leg cocking and early downswing), than in arc formation or late downswing (P < 0.008; d = 0.09–1.5).

The kicking thigh gained more energy during arc formation and leg cocking than the downswing ($P < 0.008$; $d = 0.9–2.0$). This energy was mostly from JPs at the hip (i.e., passive transfer from pelvis) before SFTD, and then from concentric work by the hip MP afterwards (Figure 4 & Figure 5). Kicking thigh energy then flowed through the kicking shank to reach the distal foot during the downswing, with the foot gaining more energy in late downswing than in any other phase ($P < 0.008$; $d = 0.6–1.2$). Although a large MP at the knee added energy to the shank during early downswing, these transfers were largely predominated by passive JPs (Figure 5).

Discussion and implications

The primary aim of this study was to investigate whole-body energy transfer strategies during fast and accurate football instep kicking. The main findings were twofold. First, in support of hypothesis a), energy was transferred from the support leg and torso into the pelvis during tension arc formation and leg cocking (Phases 1 & 2) and energy was redistributed from the pelvis to the kick leg during the downswing (Phases 3 & 4) (Inoue et al., 2014; Naito et al., 2010). However, in opposition to hypothesis b) and previous inferences (Fullenkamp et al., 2015; Langhout et al., 2015) energy was not transferred directly from the torso to pelvis during the downswing (Phases 3 & 4). Second, in support of hypothesis c), these energy transfers were positively associated with kicking foot velocities at BCS (Table 1; Figure 3). Taken together, these findings further highlight the importance of whole-body function during instep kicking. While comparison with similar investigation of upper body skills is difficult (Aguinaldo & Escamilla, 2019; Howenstein et al., 2019; Iino & Kojima, 2016; Martin et al., 2014), this study agrees skilled instep kicking is reliant on efficient transmission of energy generated by the larger more proximal and ground contacting segments to the smaller more distal segments of the kick leg. The following sections describe these energy transfer strategies in detail and provide recommendations to inform technical and/or strength and conditioning training practices.

Support leg and pelvis

In agreement with previous research that noted the importance of support leg and pelvis function during instep kicking (Augustus et al., 2017; Inoue et al., 2014; Naito et al., 2012), the current study showed the support leg thigh was the largest contributor to pelvis energy during the kick (Figures 4 & Figure 5), and these transfers were moderately associated with kicking foot velocities (Table 1). While it has been suggested SFTD initiates the downswing by converting energy gained during the approach to pelvic rotations (Augustus et al., 2017; Inoue et al., 2014; Lees et al., 2009; Naito et al., 2012) and adopting a more rigid support leg may enable faster pelvic and swing leg velocities (Augustus et al., 2017), the current study is the first to confirm the kinetic link between the support leg and pelvis is predominated by passive energy transfers. Similar 'blocking' of the stance leg has been advocated in other sports (e.g., cricket fast bowling; Ferdinands et al., 2010 and baseball pitching; Howenstein et al., 2019) to elicit efficient energy transfer and improved performance (i.e., faster ball release velocities). Given the consistent associations between support leg eccentric work, energy redistribution and faster swing leg velocities, coaches might consider training players to minimise hip and knee flexion (i.e., energy absorption) following SFTD. Developing the reactive (eccentric) capabilities of the quadriceps and hip extensors and improving support hip mobility might serve to maximise distal-proximal energy transmission and optimise conditions for pelvic and kick leg rotations during the downswing. Indicative strength training exercises are provided in Table 2 and supplementary material.

However, it is important to note the support leg should also function to create the stable base needed for an accurate kick (Kellis et al., 2004; Lees et al., 2009). Given this constraint, and that energy transfers from support thigh to pelvis only accounted for ~50% of variation in foot velocities at BCS (Table 1), it may be beneficial for a player to regulate the magnitude of this transfer. Faster approaches (i.e., greater whole-body energy at SFTD) might necessitate a less rigid support leg (> flexion and energy absorption) to ensure a coordinated kick, whereas slower approaches (i.e., less whole-body energy at SFTD) might necessitate a stiffer support leg (< flexion and energy absorption) to achieve the same outcome (Augustus et al., 2017). Training practices that incorporate varying approach conditions (e.g., manipulating approach angle, velocity or support foot placement) might help players learn to optimise this trade-off between energy transmission and movement stability and develop a technique that is robust to different match play situations. For example, Gaspar et al. (2019) recently applied a differential learning model (i.e., deliberately restricted torso and/or arm motion during the kick) and Palucci Vieira et al. (2019) manipulated environmental constraints (i.e., used a rolling or bouncing ball) to promote adaptable movement strategies in young players.

Torso, pelvis and kick leg

Similar to the support leg, energy transferred from the torso to pelvis early in the kick (Phases 1 & 2) was redistributed to the kick leg during the downswing (Phases 3 & 4), and

Table 2. Key mechanical interactions for optimising energy transfers during instep kicking, descriptions of their indicative segment and (or) joint actions and example exercises for training each interaction. Videos showing examples of each exercise are provided in the supplementary materials (insert link to supplementary material here).

Mechanical interaction	Indicative segment and (or) joint actions (and energy transfer mechanisms targeted)	Example exercises
Support leg 'blocking'	Resist support knee and hip flexion following support foot touchdown (minimise eccentric energy absorption)	1. One leg forward or lateral bound to jump back 2. Reverse plyometric lunge with contralateral knee swing 3. Split stance isometric pull
Tension arc formation	Torso extension and transverse rotation to non-kick side, and kicking hip extension (maximise eccentric pre-tensioning and stability of anterior lumbo-pelvic and hip muscles)	4. One arm overhead split snatch 5. Bulgarian split squat jumps 6. Landmine split jerk
Tension arc release	Torso flexion and transverse rotation to kick leg side, and kick leg hip flexion and adduction (maximise simultaneous concentric work)	7. Resisted cable kicks with torso rotations 8. Medicine ball lunge throw with counter-rotation 9. Single leg cross mountain climber

these transfers were associated with kicking foot velocities at BCS (Table 1). Previous research has advocated upper body motion as important for instep kicking performance (Fullenkamp et al., 2015; Langhout et al., 2015). However, given formation and release of a 'tension arc' between the torso, pelvis and kick leg functions to enable fast foot velocities (Naito et al., 2010; Shan & Westerhoff, 2005), it was surprising energy was only transferred proximo-distally during tension arc formation and leg cocking. These transfers were dominated by JPs (~ 80% of total energy transferred) and supports that energy should be passively distributed to the pelvis during the kicking stride (Naito et al., 2012). In addition to creating optimal conditions for concentric work to be performed during the downswing (i.e., Phases 3 & 4; Shan & Westerhoff, 2005), a key function of tension arc formation might also be to eccentrically stabilise the lumbo-pelvic and kicking hip joints. Lees et al. (2009) previously remarked that dynamic stability created between the pelvis and torso balances the forces experienced by the body so not perturb the kicking motion, and it seems appropriate to recommend this action should facilitate passive energy transfers as well. Coaches and practitioners might incorporate exercises that replicate tension arc formation when designing strength and conditioning programmes. Specifically, movements that induce fast and controlled eccentric pre-lengthening of the anterior torso, pelvic and kicking hip muscles might be particularly effective for training dynamic stability during the kicking motion (Table 2 and supplementary material).

In opposition to hypothesis b) and previous research (Fullenkamp et al., 2015; Langhout et al., 2015; Naito et al., 2012), concentric lumbo-pelvic work performed as the tension arc was released was not transferred to supplement kick leg energies during the downswing (Phases 3 & 4). This discrepancy may be because the segment power analyses only accounted for energy transferred between adjacent segments (Gordon et al., 1980), and could not derive contributions from non-adjacent sources. Rather than deliver energy to the kick leg sequentially through the kinetic chain, the torso may become remotely coupled with the kicking knee as it extends towards BCS (Naito et al., 2010; Zajac et al., 2002). Nevertheless, since energy transferred from the pelvis to kicking thigh was strongly associated with generation of foot velocities (Table 1), and concentric hip flexion/adduction (Dorge et al., Lees et al., 2010, 2009; Nunome et al., 2006) and torso flexion (Langhout et al., 2015) have consistently been shown to initiate proximal-to-distal kick leg sequencing (Lees et al., 2009; Shan & Westerhoff, 2005), the available evidence suggests these actions should be performed concurrently during tension arc release. Rather than focusing on developing concentric hip flexor strength in isolation (Lees et al., 2009), resistance exercises that replicate simultaneous concentric lumbo-pelvic and hip flexion (and/or adduction) (i.e., tension arc release) might be more effective for training powerful kicking motions during the downswing phases (Table 2 and supplementary material).

Furthermore, while concentric quadriceps action (i.e., a MP performed on the shank) added energy to the lower leg to initiate knee extension during early downswing (Phase 3), late downswing was predominated by passive transfers from the shank to foot (Phase 4; Figure 5). These findings support that intersegmental coordination, rather than muscular work, is the key mechanism by which the lower leg is angularly accelerated immediately before ball contact (Dorge et al., 2002; Nunome et al., 2002, 2006). As the kicking knee angularly accelerates past 90° (K90 event), extension velocities exceed the force producing capabilities of the quadriceps (Nunome et al., 2006) and any further acceleration is induced by a combination of: a) kicking thigh deceleration (i.e., negative work at the hip and knee;

Nunome et al., 2006; Putnam, 1991), b) vertical acceleration of the kicking hip (i.e., concentric work of support leg knee; Augustus et al., 2017; Putnam, 1993) and c) torso flexion (i.e., concentric work at lumbo-pelvic joint; Naito et al., 2010). From a practical perspective, these joints and/or segments should thus act in a manner which complements proximal-to-distal sequencing of the kick leg. While the interactions between these mechanisms are complex and still largely unexplored, training practices similar to those proposed for the support leg (i.e., imposing environmental or physical constraints; Gaspar et al., 2019; Palucci Vieira et al., 2019) might enable players to explore different coordination patterns and develop effective movement strategies.

Whereas a strength of the present study was that it highlighted how and when energy is generated, absorbed and transferred through the body during instep kicking, limitations are that it could not identify: (a) whole-body dynamic factors that *cause* the observed kinematics and/or performances or (b) whole-body inter-segmental coordination patterns. Regarding the former, induced power or acceleration analyses (Neptune et al., 2001) could be used to quantify the relative contributions of the support leg, torso and pelvis to foot powers or velocities. Regarding the latter, non-linear analyses (e.g., functional principal components analyses; Warmenhoven et al., 2019) could be used to elucidate the coordination patterns between these remote segments and the kicking leg. Such studies would be invaluable to help clarify (a) the features of instep kicking that contribute most performance (i.e., foot/ball speeds), (b) the different intra- and inter-individual movement strategies that experienced players use to perform fast yet accurate kicks and (c) non-efficient energy transfer strategies during kicking that are associated with injurious movement patterns (e.g., Martin et al., 2014). A further limitation was the relative simplicity of the kicking task (kick over 4 m for speed and accuracy). During match play, instep kicks are generally performed over longer distances (10–70 m; Pollard et al., 2004), so the ecological validity could be questioned. However, the necessity of including the force platform for inverse dynamics calculations meant the study was constrained to the laboratory and future research might replicate the study in an environment that more closely matches match play situations. Finally, we acknowledge that alternative energy transfer strategies likely exist for different cohorts of footballers (e.g., professionals, females) and future research might replicate this work to produce tailored practical recommendations for these groups.

Conclusions

This study has highlighted the importance of whole-body function during football instep kicking. Energy transferred from the support leg and torso early in the kick (i.e., during arc formation and leg cocking) was used to supplement pelvis and kick leg energies during the downswing, and the magnitude of these transfers was associated with faster foot velocities. Of particular importance were: (a) regulating support leg energy absorption following SFTD to induce pelvic rotations, (b) eccentric formation and concentric release of a ‘tension arc’ between the torso, pelvis and kicking hip, and (c) coordinated proximal to distal sequencing of the kick leg during the downswing. Knowledge of these strategies can help inform empirically grounded technical and/or strength and conditioning training programmes. For example, resistance exercises that replicate the demands of the highlighted mechanical interactions could be used to develop more powerful kicking motions (Table 2 and supplementary material). Furthermore, training practices that allow players to explore varying energy transfer strategies (e.g., by applying task or environmental constraints) might facilitate development of movement patterns that are robust to different match play situations.

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No potential conflict of interest was reported by the author(s).

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