**Choice of low-pass filter influences practical interpretation of ball kicking motions: the effect of a time-frequency filter method**

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**Abstract**

When studying ball kicking, conventional low-pass filters may distort kick leg kinematics near the time of foot-to-ball contact, leading to flawed practical interpretation of the skill. Time-frequency filters are a viable alternative, but are not widely used. This study compared a fractional Fourier filter (FrFF) with conventional filters (CF) methods for estimating common parameters used to define kicking performance. Instep kicks from 23 experienced soccer players were captured by 3D motion analysis (1000Hz), and kick leg foot velocities, knee angular velocities and ankle dorsi-plantarflexion angles compared between the FrFF and variations of a Butterworth CF. The FrFF and CFs using a higher cut-off frequency (> 70 Hz) successfully detected lower leg motion prior to, during and following impact, whereas CFs with low cut-off frequencies (< 20Hz) attenuated motion near impact. Truncating data at impact provided valid pre-impact kinematics, but ignored information thereafter. Rather than decelerating the lower leg to conserve accuracy, ‘kicking through the ball’ should be considered a valid coaching cue. Further, controlling ankle plantarflexion to ensure efficient impact mechanics may be important for skilled kicking. Practitioners should consider how choice of filter will affect their data, and use of time-frequency methods can help inform empirically grounded coaching practices.

**Keywords**

Soccer, football, instep kick, fractional Fourier filter, impact.

**Introduction**

Camera-based motion analyses of ball kicking skills (e.g. AFL/NFL punt, soccer instep, rugby place kicks) have been criticised for their inability to accurately represent kick leg kinematics during foot-to-ball contact (Nunome, Lake, Georgakis, & Stergioulas, 2006; Nunome, Ball, & Shinkai, 2014). If marker trajectories are conventionally low-pass filtered (CF; i.e. Butterworth filter with cut-off frequency 6 - 20Hz), derivative data (i.e. velocities and accelerations) may contain considerable error near the time of impact (Knudson & Bahamonde, 2001), and practical evaluation of the skill may be flawed (Nunome, Lake, et al., 2006; Nunome et al., 2014). To maximise the translational value of research to an applied setting, it is essential any low-pass filtering maintains optimal signal to noise ratios during both swing (i.e. pre- and post-impact) and foot-to-ball contact (i.e. during impact), so estimation of kinematic parameters used to define performance are valid over the entire kick. However, CF methods that erroneously ‘filter through’ foot-to-ball contact and distort kinematic parameters near the time of impact are still prevalent (De Witt & Hinrichs, 2012; Katis & Kellis, 2011; Katis, Kellis, & Lees, 2015; Lees, Steward, Rahnama, & Barton, 2009; Sinclair et al., 2014). The most prominent alternative has been to truncate displacement signals before the start of impact, and either extrapolate (e.g. Apriantono Nunome, Ikegami, & Sano, 2006; Nunome, Ikegami, Kozakai, Apriantono, & Sano, 2006) or reflect the final portion of the signal prior to filtering (e.g. Ball, 2011; 2013). While such methods can ensure valid pre-impact kinematics (Knudson & Bahamonde, 2001), a limitation is they exclude information both during and following the impact, and thus restrict exploration of these key phases of the kick.

An alternative is to use a time-frequency low-pass filter (TFF). The premise of a TFF is to increase the filter cut-off frequency when the impact induces deceleration of the impacting foot to ensure valid kinematics before, during and after collision with the ball. Nunome, Lake et al. (2006) used a TFF based on the Wigner distribution (Giakas, Stergioulas, & Vourdas, 2000) to accurately represent lower leg kinematics during soccer instep kicking, but few studies have adopted the technique. This may be because the method uses a complex, non-linear algorithm that requires the user to manually select filter parameters to obtain an optimal filter solution. More recently, a newer iteration of TFF, the fractional Fourier filter (FrFF; Gerogakis & Subramaniam, 2009), has also been shown to reduce error compared to CFs when estimating lower leg marker accelerations during instep kicking (Augustus, Amca, Hudson, & Smith*,* 2020). The FrFF may be preferable over the Wigner TFF (Giakas et al., 2000) as it: a) employs an automated, linear algorithm that processes marker trajectories in consecutive fractional Fourier domains, and b) selects filter parameters according to the physical characteristics of the signal (i.e. are directly determined by the duration and magnitude of the impact; Georgakis & Subramaniam, 2009).

However, it is not currently known how the FrFF influences practical interpretation of key parameters used to define kicking performance. For example, foot deceleration before impact has been advocated as an accuracy enhancing strategy (Barfield, Kirkendall, & Yu, 2002; Dorge, Andersen, Sorensen, & Simonsen, 2002; Teixeira, 1999), but this phenomenon may be the result of erroneously filtering through the impact with a CF and a low cut-off frequency (Nunome, Lake et al., 2006). High speed analyses have instead shown lower leg and foot velocities peak at the onset of ball contact (Nunome, Lake, et al., 2006; Shinkai, Nunome, Isokawa, & Ikegami, 2009), and support has thus been provided for the coaching cue of ‘kicking through the ball’ (Nunome et al., 2014). Furthermore, ankle kinematics during foot-to-ball contact are rarely reported, as it is acknowledged they are difficult to accurately represent (Lees et al., 2009; Lees, Asai, Andersen, Nunome, & Sterzing, 2010). Only recently has ultra-high-speed videography (~ 4000 Hz sampling rate) highlighted that resisting forced ankle plantarflexion, and ensuring an impact location near to the foot centre of mass (CoM) is key for efficient impact mechanics and a fast yet accurate kick (Peacock, Ball, & Taylor, 2017; Peacock & Ball, 2018; Shinkai et al., 2009). Successful application of the FrFF to the study of ball kicking might prompt a departure from the inconsistent methods that have restricted advancements in this area, and help inform empirically grounded coaching practices. The aims of this study were subsequently to a) compare the modified FrFF (Augustus et al., 2020) with common CF methods for representing lower-leg kinematics during soccer instep kicking and, b) highlight how choice of low-pass filter influences practical interpretation of ball kicking. It was hypothesised that the FrFF would successfully represent lower-leg pre- and post-impact motion, yet also be sensitive to sudden deceleration owing to foot-to-ball contact.

**Methods**

***Participants***

Twenty-three male, semi-professional soccer players volunteered for the investigation (mean ± SD; mass 78.8 ± 7.1 kg, height 1.81 ± 0.05 m, age 23.6 ± 3.9 years). All had at least 10 years competitive playing experience, were competing between Steps 1 - 7 in the English National League system, and were injury free at the time of testing. Ethical approval was granted by the University of Chichester’s local ethics committee, and participants completed written informed consent prior to data collection.

***Data Collection & Procedures***

Participants performed soccer instep kicks of a stationary ball (inflated pressure 80 kPa; Mitre Monde V12S, London, UK) ‘as fast and accurately’ as possible towards a circular target (0.5 m diameter) placed 4m away. The first ten trials that hit the target (i.e. that were accurate), were included for further analysis. Kicking motions were captured by a 10-camera, opto-electronic 3D motion analysis system (1000Hz; Vicon T40S, Vicon Motion Systems, Oxford, UK). Thirty-six reflective markers (12.6mm diameter) were attached to the lower body to produce a model comprised of bilateral feet, shanks and thighs, and a pelvis (Figure 1). Static calibration defined participant specific geometry (Havanan, 1964) and anatomical coordinate systems (ACS) for each segment. Each ACS was defined as a right-handed co-ordinate system, where Z was congruent with the long axis of the segment, X pointed to the right, and Y anteriorly (Figure 1). For the feet, the ACS origin was the mid-point between malleolus markers, for the shanks the mid-point between the medial and lateral knee markers projected onto the functional axis of knee rotation (Schwartz & Rozumalski, 2005), and the thighs the location of a functional hip joint centre (Begon, Monnet, & Lacouture, 2007). During kicking trials, the feet were tracked using calcaneus, sub-malleolar, and 5th metatarsal, respectively. Thighs and shanks were tracked using marker clusters consisting of three markers fixed to semi-rigid plastic (Cappozzo, Catani, Della Croce, & Leardini, 1995). To define joint rotations, the orientation of the distal segment ACS was expressed relative to the proximal (Grood & Suntay, 1983) using an X-Y-Z cardan rotation sequence (Lees, Barton, & Robinson, 2010). Six markers were also attached to the ball to enable calculation of ball velocity.

\*\*Figure 1 near here\*\*

***Data Processing***

The 3D motion data were exported to Visual 3D (V6, C-Motion, Rockville, USA) where ball contact start (BCS) and end (BCE) events were determined when the ball centre landmark accelerated above and below 200 m/s2, respectively (Inoue, Nunome, Sterzing, Shinkai, & Ikegami, 2014). Raw marker trajectories were then duplicated and filtered in nine filter conditions (eight CFs and the FrFF). The CF conditions were all variations of a 4th order, dual pass, zero lag Butterworth digital filter and represented methods most commonly used in ball kicking research. Trajectories were either: a) filtered through impact using the original sampling frequency (1000 Hz) with cut-off frequencies of 12, 20, 70, 100, 150 and 250 Hz, b) truncated one frame before BCS and the final 100 ms reflected prior to filtering and subsequent removal of the extrapolated region (20 Hz cut-off; BW-REF) or c) down-sampled to a rate of 250 Hz and filtered through impact with a cut-off frequency of 12 Hz (BW-DS) (Table 1). Filter cut-off frequencies of ‘filtered through’ conditions were chosen to represent studies that used either low cut-off frequencies to focus on pre-impact (swing phase) kinematics (BW-12 and BW-20; e.g. Dorge et al., 2002) or higher cut-off frequencies to focus on foot-to-ball interaction (BW-70, BW-100, BW-150 and BW-250; e.g. Peacock & Ball, 2018; Shinkai et al., 2009). The BW-REF was chosen to show the influence of truncating data before the onset of impact (e.g. Ball, 2008), and BW-DS the effect of down sampling data to a rate comparable to the majority of ball kicking literature (~100 - 400Hz; Kellis & Katis, 2007). The details of each CF are outlined in Table 1.

For the FrFF condition, marker trajectories were exported to Matlab (2017b, Natick, USA) where custom written scripts performed filtering (Georgakis & Subramaniam, 2009). The FrFF employs a triangular filter boundary that raises the cut-off frequency to retain high-frequency motion content from physical sources (i.e. deceleration of lower leg) during impact (Georgakis & Subramaniam, 2009), and boundary parameters were determined as per Augustus et al. (2020; Figure 2). Parameter *X1*represents the cut-off frequency of the non-impact phase and was set as 22 Hz (determined by residual analysis), *W* the duration of impact (calculated as time of BCE minus time of BCS), *tI* the time of maximum acceleration induced by impact and *H* the height of impact-induced expansion of the frequency content at *tI* (i.e. maximum physical frequency induced during impact). Since the physical characteristics of each marker trajectory were different, parameters *W* and *H* were optimised on a trial by trial basis. Details of the optimisation process can be found elsewhere (Augustus et al., 2020). Only tracking markers attached to the kicking foot and shank were filtered using the FrFF. Markers attached to other segments were low-pass filtered using a conventional 4th order, dual pass Butterworth digital filter (cut-off 22 Hz, determined by residual analysis). Ball markers were left unfiltered to calculate post-strike ball velocity as the mean of first derivatives of ball centre landmark over the first five airborne frames.

Dependent variables were kinematic parameters commonly used to define ball kicking performance (Lees, Asai, et al., 2010). Foot velocities were defined as the 1st derivatives (signal magnitude) of kicking foot CoM trajectories, and knee angular velocities defined as the angular velocity of the shank relative to the thigh (flexion -ve / extension +ve). Ankle range of motion (RoM) was the angular displacement of the foot relative to the shank between BCS and BCE (dorsiflexion +ve / plantarflexion -ve). Each participant’s ten trials were used to calculate a mean ± SD value per variable. Ankle RoM could not be computed for the BW-REF condition, as data were truncated at BCS.

\*\*Figure 2 and Table 1 near here\*\*

### **Statistical Analyses**

Following normality checks, one-way repeated measures ANOVAs were conducted between the nine filter conditions for each dependent variable. If sphericity was violated, the Greenhouse-Geisser adjustment was used. Alpha was Bonferroni adjusted to account for multiple comparisons (N = 5, α = 0.01) and effect sizes (partial eta squared; ηp2) classified according to Cohen (1988; 0.01 = small, 0.06 = medium, 0.13 = large). If a significant main effect was identified, planned contrasts examined pairwise differences between each CF and the FrFF (N = 5 per variable). Since this method of contrasts is non-orthogonal, the α-level of pairwise contrasts was also Bonferroni adjusted to further control Type-I error (N = 40, α = 0.001). Pairwise effect sizes were calculated according to Cohen (1988; trivial *d* < 0.2, small *d* = 0.2 - 0.5, medium *d* = 0.5 - 0.8, large *d* > 0.8). All statistical tests were conducted using SPSS (V23, IBM, New York, USA).

**Results**

Mean ± SD post-strike ball velocities and the number of kicks taken to perform 10 accurate trials were 26.1 ± 1.7 m/s and 10.5 ± 0.8 kicks, respectively. A significant main effect was observed for each dependent variable (*p* ≤ 0.001, *p* < 0.01), with large effect sizes (ηp2 = 0.808 – 0.915; Table 2). Pairwise contrasts showed the FrFF produced faster foot velocities at BCS (18.5 ± 1.1 m/s) than BW-12 (16.3 ± 0.8 m/s), BW-20 (17.2 ± 0.8 m/s), and BW-DS (16.6 ± 0.7 m/s; *p* < 0.001), with large effect sizes. The FrFF also produced faster peak foot velocities (19.0 ± 1.2 m/s) than BW-12 (17.4 ± 0.8 m/s), BW-20 (18.4 ± 0.9 m/s), BW-REF (18.6 ± 1.0 m/s) and BW-DS (17.3 ± 0.8 m/s; *p* < 0.001). Effect sizes ranged from small (0.4; BW-REF), medium (0.6; BW-20) and large (1.6; BW-12 and 1.7; BW-DS). The FrFF produced faster knee extension velocities at BCS (1840 ± 240 °/s) than BW-12 (1511 ± 187 °/s), BW-20 (1643 ± 198 °/s), BW-REF (1729 ± 223 °/s) and BW-DS (1512 ± 187 °/s; *p* < 0.001). Effect sizes were either small (BW-REF) or large (BW-12, BW-20, BW-DS). The FrFF produced peak knee extension velocities (1906 ± 254 °/s) that were faster than BW-12 (1544 ± 186 °/s), BW-20 (1693 ± 202 °/s), BW-REF (1746 ± 228 °/s), BW-DS (1528 ± 189°/s; *p* < 0.001), with medium (BW-REF) or large (BW-DS; BW-12 and BW-20) effect sizes. The FrFF produced ankle plantarflexion RoMs during ball contact (-9.9 ± 5.8º) that were greater than the BW-12 (-0.5 ± 2.1º), BW-20 (-0.5 ± 2.1º) and BW-DS (-0.6 ± 2.5º; *p* < 0.001), with large effect sizes. The CF conditions with higher cut-off frequencies (BW-70, BW-100, BW-150 and BW-250) were not different to the FrFF for any dependent variable, and showed trivial to small effect sizes (Table 2). Representative time-series changes of foot velocity, knee angular velocity and ankle angle from 40 ms before, to and 40 ms after impact are shown in Figures 3 - 5, respectively.

\*\*Table 2 and Figures 3 - 5 near here\*\*

**Discussion and Implications**

***Filter Performance***

The difficulties of measuring kick leg motion during both swing (i.e. pre- and post-impact) and foot-to-ball contact (i.e. impact) phases of ball kicking concurrently are well known (Nunome, Lake, et al., 2006; Nunome et al., 2014), and there remains a shortage of low-pass filter methods that enable valid estimation of lower-limb motion over the entire kick. The first aim of this study was thus to compare a novel TFF method (modified FrFF; Augustus et al., 2020) with CF methods for representing lower-leg kinematics during soccer instep kicking. The FrFF produced estimates of common parameters used to define kicking performance that were a) comparable to CFs using higher cut-off frequencies (i.e. BW-70, BW-100, BW-150 and BW-250; Table 2) and previous studies using higher sampling and cut-off frequencies to represent foot-to-ball impact kinematics (Nunome, Lake et al., 2006; Peacock & Ball, 2018; Shinkai et al., 2009), and b) removed high-frequency fluctuations (noise) from these parameters either side of the impact (Figures 3 - 5). The hypothesis that the FrFF would successfully represent lower-leg pre- and post-impact motion, yet also be sensitive to the sudden deceleration owing to foot-to-ball contact was thus confirmed.

The widely used reflection technique (BW-REF) also provided valid lower-leg kinematics up until the instance of BCS, but inherently removed all information during and after the impact (Knudson & Bahamonde, 2001). This method subsequently restricted evaluation of these key phases of the kick. As previously shown by Nunome, Lake, et al. (2006), ‘filtering through’ foot-to-ball contact with a CF and low cut-off frequency (< 20Hz) and/or lower sampling rate (250Hz) attenuated high-frequency motion and distorted kinematics from approximately 30 – 20 ms before and after impact. Such methods should thus be avoided in future study of ball kicking. Finally, CFs using higher cut-off frequencies (70 - 250 Hz) closely matched the raw data and FrFF for each parameter, and thus successfully represented both swing and impact phase kinematics over the entire kick (Figures 3 - 5). The BW-70 and BW-100 conditions optimally removed high-frequency noise pre- and post-impact yet also represented the impact phase well. If marker trajectories are sampled at a rate comparable to the current study (~1000Hz), a CF with cut-off in this range is thus considered sufficient if segment and (or) joint angles and velocities are the primary variables of interest. Conversely, the highest cut-offs frequencies (BW-150 and BW-250) inevitably retained and amplified more high-frequency content when velocity parameters (i.e. 1st derivatives) were calculated (Figures 3 and 4). This content would become problematic if a noisy peak was evident at the instant of BCS (i.e. artificially inflating the parameter’s magnitude) or if this noise is further amplified when 2nd derivative or kinetic parameters are of interest (i.e. accelerations and joint moments).

To emphasise this point, foot accelerations (signal magnitude of 2nd derivative CoM trajectories) for the same representative trial as Figures 3 -5 were calculated in each FrFF, BW-70, BW-100, and BW-150 condition (Figure 6). The FrFF provided a noise free solution before and after foot-to-ball contact yet also maintained peak accelerations occurring during impact. Conversely, the CFs displayed a clear trade-off between removing high-frequency noise pre- and post-impact, and maintaining the impact peak. The BW-70 was noise free during swing but attenuated the impact peak, whereas BW-150 provided a noisier solution during swing but better matched the FrFF during impact. This reinforces that the FrFF outperforms CF methods when higher order parameters are of interest (Augustus et al., 2020). Future research might use the FrFF in conjunction with modelling the magnitude and point of application of the ball impact force (Iga, Nunome, Sano, Sato & Ikegami, 2017) in an inverse dynamics analysis to provide valid assessment of joint moments over the entirety of a kick. To date, such analyses have been limited to pre-impact phases of the kick only (Nunome, Ikegami et al., 2006).

\*\*Figure 6 near here\*\*

Since the FrFF and CFs with high cut-off frequencies provided valid estimates of kinematic parameters commonly used define kicking performance, these methods should become more widely used. If CFs with low cut-off frequencies continue to be used, the presence of any distortion (in the case of ‘filtering through’) or omission (in the case of truncating data at BCS) of data will continue to confound attempts of the biomechanics community to successfully inform empirically grounded coaching recommendations. The following sections will discuss these issues to highlight how choice filter method influences practical interpretation of ball kicking.

***Foot Velocities***

In agreement with Nunome, Lake, et al. (2006), the current FrFF and CFs using higher cut-off frequencies (> 70 Hz) showed that when kicking for speed and accuracy, skilled soccer players tend to accelerate the foot to a peak velocity of 18 - 23 m/s at BCS, before suddenly decelerating this segment under the external force from the ball. The BW-REF also produced comparable values at BCS, which fell within the ranges reported for skilled players performing maximal effort kicks (18 - 23 m/s; Kellis & Katis, 2007; Lees, Asai, et al., 2010). Conversely, CFs that filtered through the impact with a low cut-off frequency (< 20 Hz) underestimated the peak, and foot velocities at BCS (15 – 18 m/s; Barfield et al., 2002; De Witt & Hinrichs, 2012; Katis & Kellis, 2011; Katis et al., 2015), and distorted time-series data by removing physically meaningful content from marker trajectories near the time of impact (Figure 3). In agreement with Nunome, Lake, et al. (2006), any deceleration of the foot before impact is therefore likely the result of over-filtering, rather than a strategy used to enhance accuracy (Barfield et al. 2002; Dorge et al., 2002; Teixeira, 1999).

Given this study and Nunome, Lake, et al. (2006) both showed experienced soccer players accelerate the foot into the impact phase, the trade-off between speed and accuracy might be regulated in a different way. Rather than decelerating the foot before contact, skilled players might conserve accuracy by dampening the relative velocities and amplitude of joint rotations (Urbin, Stodden, Fischman, & Weimar, 2011), or using a slower approach to afford greater control over these rotations during the kicking stride (Andersen & Dorge, 2011). This seems logical given the necessity to maximise foot velocity at the instance of BCS to produce as fast a ball velocity as possible (De Witt & Hinrichs, 2012). Coaches should be aware of these alternative strategies when prescribing training practices. However, a limitation of the current study and Nunome, Lake, et al. (2006) was the simplicity of the accuracy constraints imposed on participants (i.e. straight kicks of a stationary ball over 4 or 9 m, respectively). It is unknown if the aforementioned strategies are adopted during more complex kicking tasks, such as those performed during match play situations (e.g. kicks over longer distances or with pressure from defenders). Increasing task complexity might place greater emphasis on controlling foot velocities to ensure accuracy, but further research is needed to confirm this assumption. Any such research should use valid filter methods to elucidate how individual kickers organise their movement pattern to meet these demands.

***Knee Angular Velocities***

Knee extension velocities were also attenuated near the time of impact when a CF with a low cut-off frequency was used. The CFs using low cut-off frequencies (< 20 Hz) all produced peaks and values at BCS that agreed with previous studies using similar methods (1500 - 1700 °/s; De Witt & Hinrichs, 2012; Lees et al, 2009; Sinclair et al., 2014), whereas studies using TFF and extrapolation methods have all reported exclusively higher values in line with the current FrFF, and CFs with higher cut-off frequencies (1700 – 2100 °/s; Apriantono et al., 2006; Nunome, Lake, et al., 2006, Nunome, Ikegami, et al., 2006). Similar to foot velocities, since the current study and Nunome, Lake, et al. (2006) both showed the lower leg angularly accelerated into the impact, any deceleration observed before impact is likely due to over-filtering. However, where Nunome, Lake, et al. (2006) reported lower-leg angular velocities peaked at BCS before immediately decelerating, the current study showed knee extension velocities peaked approximately halfway through the impact (Figure 4). This discrepancy might be explained by Nunome, Lake, et al. (2006) reporting shank segment rather than knee joint angular velocity (which does not account for the relative motion of the thigh). However, since the thigh is likely to have decelerated to a stationary position by BCS (Nunome, Ikegami et al., 2006), the two parameters are directly comparable at this instance of the kick. Subsequently, this discrepancy might instead be explained by a difference in technique between the two cohorts. The participants used by Nunome, Lake, et al. (2006) may have arrested forward motion of the shank upon impact, a strategy that has previously been shown by players performing a ‘knuckle’ or ‘push’ shot (Shinkai & Smith, 2017). Conversely, the current participants may have ‘kicked through the ball’, as has been advocated by coaching literature (Wesson, 2002; Nunome et al., 2014).

Indeed, a further discrepancy was that whereas the current study showed an increase in knee angular velocity following BCE, Nunome, Lake, et al. (2006) did not. This provides additional support that the current participants ‘kicked through the ball’. Without use of valid filter methods, neither study would have been able to detect the subtle intricacies of these different strategies used to perform fast and accurate kicks. Since overall performance (in terms of ball velocity) obtained from both studies was remarkably similar (26.1 ± 1.7 vs 26.3 ± 3.4 m/s, respectively), the analyses highlight that different but equally functional movement strategies exist for skilled instep kicking. With exclusive use of lower sample rates and cut-off frequencies, this important information would have been overlooked. From a practical perspective, those players who favour ‘kicking through the ball’ might benefit from training the mechanisms that induce proximal-to-distal angular acceleration of the knee during the final stages of the downswing (e.g. Putnam 1991; Koike, Ishikawa, Willmott, & Bezodis, 2019), whereas those who arrest knee angular acceleration at BCS might focus on developing eccentric capabilities of the quadriceps and maximising the effective mass of the lower leg at BCS.

***Ankle Angular Displacement***

Due to difficulties of representing ankle kinematics during foot-to-ball contact using CF methods, the function of the ankle in ball kicking has been largely overlooked (Levanon & Dapena, 1998; Lees et al., 2009). Only recently has ultra-high-speed videography accurately described ankle motion during skilled ball kicking (Peacock et al., 2017; Peacock & Ball, 2018; Shinkai et al., 2009). In agreement with these studies, the current FrFF and CFs using higher cut-off frequencies (>70 Hz) detected between 0 - 20 degrees of ankle plantarflexion during impact under the external force of the ball, whereas this motion was completely removed when CF methods with lower cut-off frequencies were used (Figure 5). Taken together, these studies reveal the complex role of the ankle during ball kicking. Ankle orientation and RoM likely regulate the precise foot-to-ball mechanics needed for an accurate kick (Peacock & Ball, 2018), and a more rigid ankle (small RoM) and impact location near to the foot CoM have been shown as beneficial for producing a fast kick (Peacock et al., 2017). However, the large variations in ankle range of motion noted by the current study (Table 2) and Shinkai et al. (2009) may also be indicative of different strategies for ensuring a successful kick. Since the interaction between foot and ball may not always be as intended (e.g. due a misaligned foot trajectory or non-optimal impact location; Nunome et al., 2014), skilled players may subtly adjust ankle motion to ensure success. Whereas a more rigid ankle (small RoM) would theoretically impart more momentum on the ball (Peacock et al., 2017), a more compliant ankle (large RoM) might allow greater control of the post-strike ball trajectory (i.e. enhance accuracy). To highlight this point, representative examples of two kicks performed by the same participant showing these opposing strategies are shown in Figure 7 (and represented using the FrFF).

\*\*Figure 7 near here\*\*

Future use of TFFs might therefore enable identification of the different ankle strategies used by skilled kickers to ensure fast yet accurate kicks. For example, pronounced dorsiflexion after the ball leaves the foot (Figures 5 and 7) might be indicative of a strategy to resist forced plantarflexion during impact (Peacock & Ball, 2018). However, it is unknown whether this motion is due to concentric contraction of the dorsiflexors, or by passive stretch-shorten of ligaments and tendons. Given the short period over which any neuromuscular changes would need to occur (~10 ms; Todd et al., 2007), it is unlikely kickers can change contraction patterns to alter ankle function during foot-to-ball contact. Ankle rigidity is instead likely regulated during the pre-impact downswing phase (i.e. in preparation for impact; Peacock et al., 2017). As discussed previously, TFF methods (i.e. valid segment acceleration estimates) could be combined with ball impact force modelling (Iga et al., 2018) to enable assessment of the magnitude and timing of ankle joint moments during the kick. Such an analysis would permit evaluation of how skilled players: a) control ankle rigidity and b) mitigate against non-optimal foot-to-ball impact mechanics. This information could ultimately be used to assess the effectiveness of training interventions aimed at improving ball impact efficiency.

Limitations of this study include that it was not possible to determine the ‘real’ (i.e. entirely noise free) values for each dependent variable. The optimal filter solution was thus considered as that which did not attenuate maxima and minima yet removed high-frequency content in the time-series data. Further, systematic comparison of different filter methods at the down sampled rate of 250 Hz was not performed. Since the coefficients of a Butterworth low-pass filter are determined by the ratio between cut-off frequency and sample rate, different cut-off frequencies would likely be ‘optimal’ at this lower sampling rate. Finally, it was not possible to directly compare the FrFF to other TFFs (e.g. Nunome, Lake et al., 2006), as the algorithms are not publicly available. Future research must research ensure TFFs are made available for use with common biomechanics data processing packages.

**Conclusion**

The FrFF performed comparably to CF methods using a high cut-off frequency for determining representative kick leg kinematics during soccer instep kicking. These methods provided valid estimates of foot velocities, knee angular velocities and ankle angles before, during and after foot-to-ball contact, and can thus improve the efficacy of future study of ball kicking skills. Where possible, these methods should become more widely used. However, if higher order parameters are of interest (i.e. segment and joint accelerations), the FrFF should be preferred. Despite ignoring important information following the instance of BCS, truncation and extrapolation of kinematic parameters before the onset of ball contact can provide valid pre-impact kinematics, but filtering through the impact with a CF and low cut-off frequency should be avoided. Ultimately, researchers should seriously consider how choice of low-pass filter affects practical interpretation of their data. Future use of valid filter methods can enable identification of the different strategies used by skilled kickers to optimise their movement patterns, and help inform empirically grounded training practices.

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**Tables**

Table 1. Details of conventional filter (CF) conditions. Each condition was chosen to represent a method used within the ball kicking literature (see text for rationale of choosing each condition).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Conventional Filter Condition | Filter Type | Sample Rate (Hz) | Cut-Off Frequency (Hz) | Impact Phase | Start and End Endpoint Extrapolation |
|
| BW-12 | 4th order, dual pass Butterworth | 1000 | 12 | Filtered through | One-hundred frames reflection, removed following filter application |
|
| BW-20 | 4th order, dual pass Butterworth | 1000 | 20 | Filtered through | One-hundred frames reflection, removed following filter application |
|
| BW-70 | 4th order, dual pass Butterworth | 1000 | 70 | Filtered through | One-hundred frames reflection, removed following filter application |
| BW-100 | 4th order, dual pass Butterworth | 1000 | 100 | Filtered through | One-hundred frames reflection, removed following filter application |
| BW-150 | 4th order, dual pass Butterworth | 1000 | 150 | Filtered through | One-hundred frames reflection, removed following filter application |
| BW-250 | 4th order, dual pass Butterworth | 1000 | 250 | Filtered through | One-hundred frames reflection, removed following filter application |
|
| BW-REF | 4th order, dual pass Butterworth | 1000 | 20 | Truncated one frame before ball contact initiated | One-hundred frames reflection, removed following filter application |
|
| BW-DS | 4th order, dual pass Butterworth | 250 | 12 | Filtered through | Twenty-five frames reflection, removed following filter application |
|

Table 2. Mean ± SD values for each variable calculated in each of the nine filter conditions, and pairwise contrasts of each conventional filter compared to FrFF. ES = effect size, BCS = ball contact start. RoM = range of motion.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | FrFF | BW-12 | BW-20 | BW-70 | BW-100 | BW-150 | BW-250 | BW-REF | BW-DS |
|  |
| Foot Velocity at BCS (m/s) | Mean ± SD | **18.5 ± 1.1** | 16.3 ± 0.8 | 17.2 ± 0.8 | 18.5 ± 1.0 | 18.6 ± 0.9 | 18.7 ± 1.0 | 18.7 ± 1.0 | 18.4 ±  0.9 | 16.6 ± 0.7 |
| p-value |  | <0.001\* | <0.001\* | 0.370 | 0.123 | 0.087 | 0.006 | 0.894 | <0.001\* |
| ES (*d*) |  | 2.3 | 1.4 | 0.0 | 0.1 | 0.2 | 0.2 | 0.1 | 2.1 |
|  |  |  |  |  |  |  |  |  |  |  |
| Peak Foot Velocity (m/s) | Mean ± SD | **19.0 ± 1.2** | 17.4 ± 0.8 | 18.4 ± 0.9 | 19.1 ± 1.0 | 19.3 ± 0.9 | 19.3 ± 1.2 | 19.1 ± 1.5 | 18.6 ±  1.0 | 17.3 ± 0.8 |
| p-value |  | <0.001\* | <0.001\* | 0.984 | 0.127 | 0.110 | 0.032 | <0.001\* | <0.001\* |
| ES (*d*) |  | 1.6 | 0.6 | 0.1 | 0.3 | 0.3 | 0.1 | 0.4 | 1.7 |
| Knee Extension Velocity at BCS (°/s) | Mean ± SD | **1840 ± 240** | 1511 ± 187 | 1643 ± 198 | 1865 ± 258 | 1855 ± 248 | 1857 ± 240 | 1852 ± 246 | 1729 ± 223 | 1512 ± 187 |
| p-value |  | <0.001\* | <0.001\* | 0.004 | 0.018 | 0.067 | 0.092 | <0.001\* | <0.001\* |
| ES (*d*) |  | 1.6 | 0.9 | 0.1 | 0.1 | 0.1 | 0.0 | 0.5 | 1.5 |
|  |  |  |  |  |  |  |  |  |  |  |
| Peak Knee Extension Velocity (°/s) | Mean ± SD | **1906 ± 254** | 1544 ± 186 | 1693 ± 202 | 1889 ± 246 | 1941 ± 271 | 1954 ± 272 | 1935 ± 241 | 1746 ± 228 | 1528 ± 189 |
| p-value |  | <0.001\* | <0.001\* | 0.041 | 0.114 | 0.141 | 0.047 | <0.001\* | <0.001\* |
| ES (*d*) |  | 1.7 | 0.9 | 0.1 | 0.1 | 0.2 | 0.1 | 0.7 | 1.7 |
|  |  |  |  |  |  |  |  |  |  |  |
| Ankle RoM During Impact (°) | Mean ± SD | **-9.9 ± 5.8** | -0.5 ±  2.1 | -0.5 ±  2.1 | -10.1 ± 5.3 | -10.2 ± 5.7 | -10.4 ± 5.7 | -10.5 ± 5.3 | N/A | -0.6 ±  2.5 |
| p-value |  | <0.001\* | <0.001\* | 0.464 | 0.567 | 0.573 | 0.246 | N/A | <0.001\* |
| ES (*d*) |  | 2.1 | 2.1 | 0.0 | 0.1 | 0.1 | 0.1 | N/A | -2.1 |

**Figure Captions**

Figure 1. Lower body marker set and anatomical coordinate system for each segment. ASI = anterior superior iliac spine, IC = iliac crest, GT = greater trochanter, TH = thigh, FEM = femoral epicondyle, SH = shank, MAL = malleolus, MET = metatarsal, LAT = lateral, MED = medial.

Figure 2. Comparison showing constant cut-off frequency (*fc*) of conventional filter and time-varying *fc* of the fractional Fourier filter. *X1* = cut-off frequency of swing phase, *W* = width of impact, *H* = height of impact (maximum cut-off frequency), *ti* = time of impact centre*.*

Figure 3. Representative changes in foot velocity (m/s) from 40 ms before ball contact start (shown as vertical line at time = 0ms) to 40 ms after ball contact end (shown as vertical line at time = 11ms) in each filter condition. Foot velocities calculated from raw displacements are shown by the grey line in each plot, and filtered data as the black line (condition shown above each plot). Checked markers in the BW-DS condition indicate data sampled every 4 ms (i.e. 250 Hz).

Figure 4. Representative changes in knee angular velocity (°/s; +ve = extension and -ve = flexion) from 40 ms before ball contact start (shown as vertical line at time = 0 ms) to 40 ms after ball contact end (shown as vertical line at time = 11ms) in each filter condition. Knee angular velocities calculated from raw displacements are shown by the grey line in each plot, and filtered data as the black line (condition shown above each plot). Checked markers in the BW-DS condition indicate data sampled at every 4 ms (i.e. 250 Hz).

Figure 5. Representative changes in ankle angle (°; +ve = dorsiflexion and -ve = plantarflexion) from 40 ms before ball contact start (shown as vertical line at time = 0ms) to 40 ms after ball contact end (shown as vertical line at time = 11ms) in each filter condition. Ankle angles calculated from raw displacements are shown by the grey line in each plot, and filtered data as the black line (condition shown above each plot). Checked markers in the BW-DS condition indicate data sampled every 4 ms (i.e. 250 Hz).

Figure 6. Representative changes in foot acceleration (m/s2) from 40 ms before ball contact start (shown as vertical line at time = 0ms) to 40 ms after ball contact end (shown as vertical line at time = 11ms) in each FrFF, BW-70, BW-100 and BW-150 condition. The Raw and BW-250 conditions are not shown as these contained excessive high-frequency noise that made the signals indiscernible.

Figure 7. Representative example showing variation in ankle strategy used for two trials performed by the same participant. The right-hand trial shows a rigid ankle strategy (small plantarflexion RoM), whereas the left-hand trial shows a compliant ankle strategy (large plantarflexion RoM) during foot-to-ball contact (shown by vertical dashed lines at 0 and 11 ms).