A COMPARISON OF UNMATCHED AND MATCHED FILTERING APPROACHES FOR KNEE JOINT STIFFNESS CALCULATION DURING RUNNING

Zhenyuan Zhang and Mark Lake

School of Sport and Exercise Science, Liverpool John Moores University, Liverpool, United Kingdom

This study compared typical measures of knee joint moment, angle and stiffness in eight recreational runners during distance running after digitally filtering ground contact force and lower limb motion data using 20-20 Hz and 50-8 Hz cut-off frequencies, respectively. The matched 20 Hz approach clearly removed some higher frequency oscillation signals in the knee moment curves and produced a better linear regression fit to calculate joint stiffness from the knee moment-angle relationship. However, knee joint stiffness values over the first half of running stance were no different between the two filtering approaches. It remains to be determined whether improved linear fit can lead to greater sensitivity in the joint stiffness estimations to detect changes that may result from factors such as fatigue or footwear interventions.

KEYWORDS: filtering, cut-off frequencies, kinematics, kinetics, knee joint stiffness.

INTRODUCTION: Signal processing is necessary before performing inverse dynamics analysis in biomechanical research. However, it is sometimes a challenge to reduce noise in kinematic marker trajectories and force platform data with appropriate digital filtering, while also preserving any high frequency signal content. Recent literature (Derrick et al., 2020) indicated that matched low-pass filter cut-off frequencies were required to filter raw kinematic and kinetic data for joint moment calculations using inverse dynamics, as discrepant frequency content between those two sets of data may lead to impact-like artefacts in the joint kinetics. Moreover, Mai and Willwacher (2019) proposed to filter kinetic and kinematic data using matched cut-off frequencies around 20 Hz as a compromise between avoiding artefacts in the joint moment data and preserving high frequency content during running. Joint moment is also used in the calculation of lower limb joint stiffness. Joint stiffness is defined as the ratio of the external loading to the change in joint angular deformation. It has been shown to modulate the landing strategy and musculoskeletal system adaptation in human movements such as running and jumping (Gruber et al., 2021). A spring-like model, which examines changes in the linear fit of the slop of joint moment-angle curve, has been commonly used to quantify joint stiffness during running (Hamill et al., 2014). Typically, unmatched filtering approaches have been used in the literature before the calculation of joint stiffness, but more recently matched approaches have been employed (Gruber et al., 2021). Different filtering approaches may modify both joint moment and angle, leading to different stiffness values. Therefore, the purpose of this study was to investigate if matched and unmatched filtering approaches elicit changes in knee joint stiffness and other loading-related variables during running. It was hypothesized that the different filtering approaches would cause changes in joint moment curves, and this would consequently lead to significant changes in measures of joint stiffness.

METHODS: Eight male recreational runners (23 ± 2.7 years, 1.81 ± 0.04 m, 76 ± 7.9 kg, weekly running mileage > 10 km) participated, while wearing standard running shoes (UK 9, FuelCell, New Balance, USA). All participants were free of injury in the past 6 months and consent forms were obtained prior to data collection. A 40 m runway constructed with a force plate (1500 Hz, Kistler AG, Switzerland) in the middle and surrounded by an 8-camera motion capture system (100Hz, Qualisys AB, Sweden) was deployed to record ground reaction force and 3D motion data. 11 retro-reflective markers and 2 lightweight carbon fibre plates that consist of 4 non-colinear markers were attached on each participant's right leg to define lower limb segments to track their motion. Timing gates (Brower System, USA) were set 5 m apart around the force platform to monitor the running speed within 4.5 m/s ± 5%. After 5 minutes of warm up, participants were instructed to run along the runway and 5 successful trials were collected per participant. Enough time for rest was given to all participants. For the data processing, raw ground reaction force (GRF) data and marker trajectories were synchronized using QTM software (Qualisys AB, Sweden) and then filtered using a 4^{th} order, zero lag, low-pass Butterworth filter. For the unmatched filtering, cut-off frequencies were set at 50 Hz for GRF and 8 Hz for marker trajectories (Borgia and Becker, 2019), while the matched filtering used a 20 Hz cut-off frequency for both (Mai and Willwacher, 2019). A 3D model consists of the right thigh, shank and foot segment was built using Visual 3D (C-Motion, Inc, USA), where the knee joint moment, angle and angular velocity were calculated using traditional Newton-Euler inverse dynamics and X-Y-Z Cardan rotation sequence. Impact peak was represented by the first peak of vertical GRF, where the max loading rate was calculated as the maximal slope of vertical GRF curve from touchdown to impact peak. A linear regression line was fitted to the knee moment-angle curve starting from touchdown to the peak knee flexion angle (i.e. mid stance). The event of touchdown was identified using a 20 N threshold of vertical GRF, where the knee joint angle was defined as the angle between shank segment relative to the orientation of thigh segment. The slope of regression line represents the knee joint stiffness (see figure 2 for a typical trial). To further assess the goodness of linear fit in knee joint moment-angle curve, root-mean-square error (RMSE) that adopted in previous literature (Nigro et al., 2021) was also calculated . Each variable in successful trials was averaged for each subject. A paired t-test was performed to statistically examine the difference caused by two filtering approaches. A two tailed alpha level of $p = 0.05$ was set to indicate statistical significance.

RESULTS: As shown in figure 1, no significant difference between unmatched and matched filtering for knee joint stiffness was found ($t = 1.300$, $p = 0.23$). There was a significant different between unmatched and matched filtering for RMSE ($t = 4.318$, $p < 0.05$). In table 1, the impact peak and max loading rate of vertical GRF filtered by 50 Hz was significantly higher than those of being filtered by 8 Hz ($p < 0.05$). No significant differences were detected in max knee joint angle ($p = 0.28$), max knee flexion moment ($p = 0.28$) and only subtle changes in the evolution of the knee angle curves were found between two filtering approaches. Compared to using an 8 Hz cut-off frequency, max knee flexion velocity significantly increased with 20 Hz cut-off frequency filtering ($p < 0.05$).

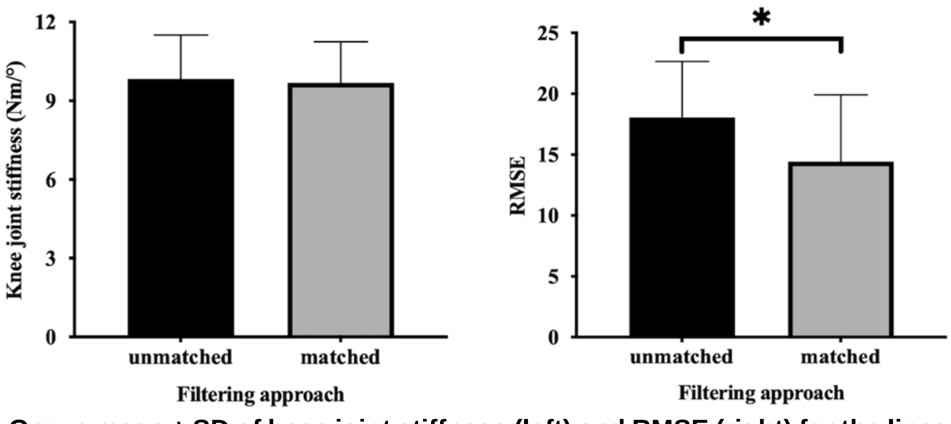

Figure 1: Group mean ± SD of knee joint stiffness (left) and RMSE (right) for the linear regression fit between two filtering approaches.

Table 1: Group mean ± SD of impact peak, max loading rate, max knee angle, max knee flexion velocity and max knee flexion moment.

	unmatched filtering	matched filtering	*t*	*p*
Impact peak (BW)	2.2 ± 0.3	2.1 ± 0.3	3.538	< 0.05
Max loading rate (BW/s)	136.8 ± 44.0	98.7 ± 32.5	6.548	< 0.05
Max knee angle (°)	48.4 ± 5.5	48.7 ± 5.0	1.177	= 0.28
Max knee flexion velocity (°)	477.2 ± 46.9	561.2 ± 83.9	4.678	< 0.05
Max knee flexion moment (Nm)	275.9 ± 65.1	277.1 ± 65.3	1.178	= 0.28

Note: impact peak and max loading rate were normalized to bodyweight and filtered by 50 Hz cut-off frequency for unmatched approaches, where max knee angle and flexion velocity were filtered by 8 Hz cut-off frequency for unmatched approaches.

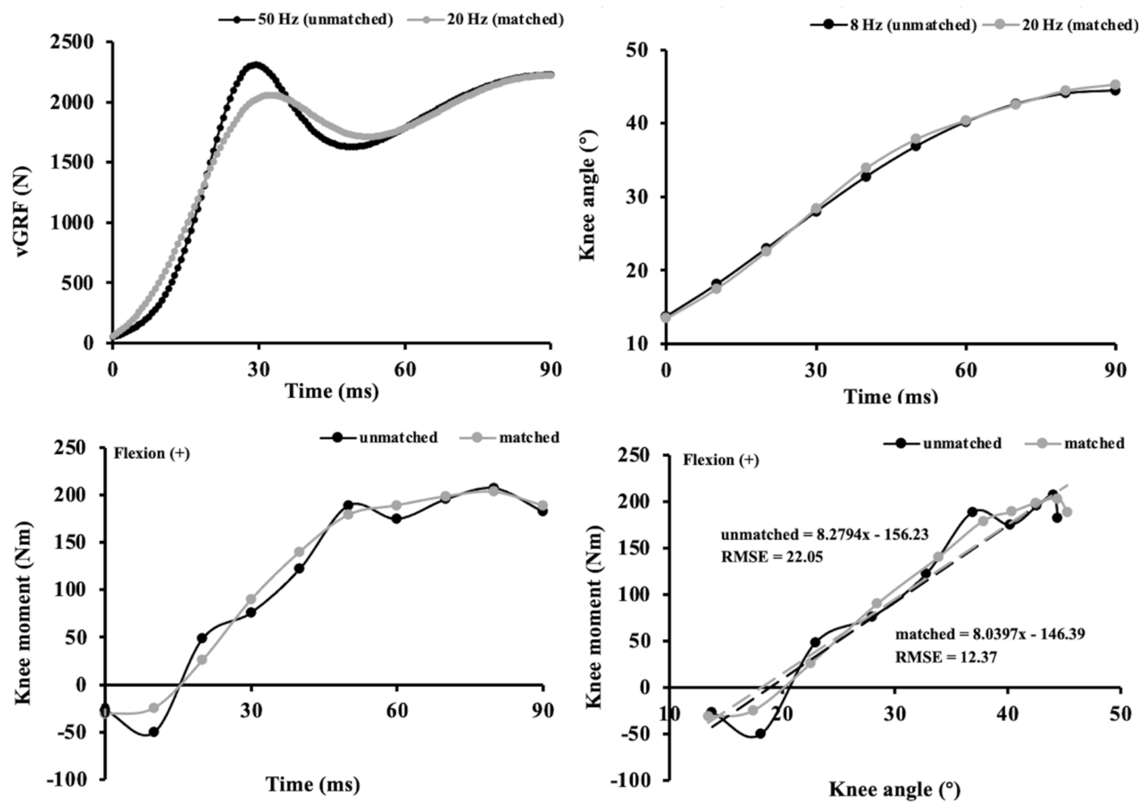

Figure 2: Vertical GRF (top left), knee angle-time (top right), knee moment-time (bottom left) and knee moment-angle (bottom right) curves from touchdown to the max knee flexion for a representative trial on one subject. Except the knee angle-time curve, others were smoother using 20 Hz matched cut off frequency compared with unmatched counterparts.

DISCUSSION: The aim of this pilot study was to determine whether unmatched and matched filtering approaches influence knee joint kinetics and kinematics, and hence produce different knee joint stiffness measures during running. Knee joint stiffness remained unchanged between the two filtering approaches which was partially contrary to the hypothesis. Vertical GRF curve (Figure 2) was clearly over-smoothed within the matched filtering that used a lower cut-off frequency (20 Hz). This resembled to literature (Mai and Willwacher, 2019) and led to a reduced impact peak and max loading rate, compared to the unmatched counterpart (50 Hz). The results also indicated that the selected cut-off frequencies caused much less influence on the knee kinematics. Since cut-off frequencies for knee kinematics increased from unmatched to matched filtering (8 Hz to 20 Hz) which means some noise might flow in, but the typical knee angle-time curve (Figure 2) and max knee angle (Table 1) appeared to be similar between the two filtering approaches. However, when knee angle was differentiated with respect to time, the effect of different cut-off frequencies was amplified which resulted in significantly increased max knee angular velocity from 8 Hz to 20 Hz cut-off frequencies. Partially contrary to previous studies (Bezodis et al., 2013; Kristianslund et al., 2012), the peak knee flexion moment during first half of stance remained same between two filtering approaches in present study (Table 1). This might be explained by the differences in cut-off frequencies selected for filtering GRF and kinematic data between present and present studies. While the knee moment-time curve displayed some oscillatory behaviour characterized with higher frequencies under the unmatched filtering approach, whereas the matched counterpart was relatively smoothed. Mai and Willwacher (2019) indicated the discrepancy in suppressed segment accelerations and the remained vertical GRF impact peak for unmatched filtering could result in those fluctuations in knee moment-time curve. Therefore, it is suggested to analyze GRF data separately to calculate peak impact and loading rate using a higher cut-off frequency (i.e. 50 Hz or above) that retains real physiological contents. While, in subsequent joint moment calculation, the cut-off frequency for GRF and kinematics should be matched at the same level around 20 Hz to minimize fluctuations (the protocols adopted by Gruber et al. (2021) and Mai et al. (2019)). Nevertheless, the matched filtering only flattened spikes in knee moment-angle curve but did not affect its overall shape. Therefore, the slope of regression line (Figure 2) remained similar between two filtering approaches. In other words, no matter the cut-off frequencies for filtering are matched or not, it might be a less sensitive computational method for knee joint stiffness settings during the first half of stance. As there were some previous studies (Verheul et al., 2017) attempted to narrow down the time window of first half of stance by splitting it into sub-phases and adopted other computational method for knee joint stiffness settings associated with sub-phases respectively. Moreover, comparison of knee stiffness values to previous studies was not made as they are highly dependent on the running speed. As another result of smoothing under matched filtering, the non-linearity of knee moment-angle curve reduced (i.e. reduced RMSE), thus significantly improving the goodness of linear fit and implicating there might be an increased sensitivity to elicit changes among experimental conditions (e.g. different shoe conditions). Further limitation of this study should be acknowledged as only a few cut-off frequencies were selected, while consideration of validation of the matched filtering approach and a more advanced modelling are needed in future studies.

CONCLUSION: Matched cut-off frequencies for marker trajectories and force platform data reduced oscillations in the knee joint moment curves during running but estimations of knee joint stiffness during the first half of running stance were not influenced. However, the linear fit of the joint moment-angle relationship was improved with the matched filtering approach. This could possibly lead to better sensitivity for investigating subtle joint stiffness changes associated with (e.g. footwear or fatigue), but should also be adopted cautiously. GRF-related parameters for impact during running require a separate higher frequency filtering solution.

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