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Influence of signal filtering and sample rate on isometric torque – time parameters using a traditional isokinetic dynamometer

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ABSTRACT

Isometric force- or torque-time parameters are commonly reported in the research literature. The processing methods of the electronic dynamometer-derived signal may influence the outcome measures. This study determined the influence of filtering and sample rate (SR) on isometric torque-time parameters and provides specific signal processing recommendations for future studies. Twenty-three subjects performed 49 isometric maximum voluntary contractions (MVCs) of the knee extensors on an isokinetic dynamometer. Outcome measures included peak torque (PT), and rate of torque development at peak (RTDPEAK), 50 (RTD50) and 200 (RTD200) ms for seven filter conditions including low-pass filter cutoffs at 5, 10, 20, 50, 100 and 150 Hz and a notch filter at 100 and 200 Hz. Comparisons were also made across four SR conditions at 100, 500, 1000 and 2000 Hz. The RTDPEAK variable was markedly changed (–5.4 to –37.9%) for all filter frequencies compared to the 150 Hz condition and the RTD50 variable was altered for all frequencies between 50 and 5 Hz. No differences were found for RTD200. For SR, compared to the 2000 Hz condition, differences were revealed for the 100 Hz condition for the RTDPEAK and RTD50 variables. The filtering or SR did not alter PT across any of the conditions. The filter and SR applied to the signal was capable of distorting the MVC signal and skewing the torque–time parameters, specifically for the early and maximum RTD variables of the MVC curve (RTD50 and RTDPEAK). For traditional isokinetic dynamometers, a low-pass filter cutoff of 150 Hz and a SR of at least 1000 Hz is recommended when assessing early isometric force- or torque-time MVC parameters.

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1. Introduction

The ability to produce high muscular forces is an important physiological attribute linked to optimal human movement, functional capacity, and overall health and quality of life (Westcott, 2012; Suchomel et al., 2016; Thompson et al., 2018). Moreover, the ability of muscles to produce force rapidly has been shown to be a highly necessary characteristic for optimal performance and overall enhanced physical capacity due to the time dependent nature of many human movement tasks (Aagaard et al., 2002; Maffiuletti et al., 2016).

The accurate assessment of one's muscle force production characteristics is an important means to effectively quantify, classify, and monitor across time, the status of their overall muscle function attributes – which contributes to enhanced performance and health when coupled with effective interventions. Although the

magnitude (i.e., peak force or maximum strength) of voluntary muscle force production may be assessed via a variety of assessment methods – such as dynamic constant external resistance (i.e., repetition maximum testing with weights), isokinetic modes involving concentric or eccentric muscle actions across a range of velocities, or isometric muscle actions – the ability to assess force at specified time points during the maximum voluntary contraction (MVC) necessitates the production of a force- or torque-time signal. An isometric torque – time curve is obtained from an electronic dynamometer (including commercial dynamometers, force plates or custom load cell-based instruments) from which the rapid muscle torque variables are calculated. Commonly assessed rapid muscle torque variables are the rate of torque development (RTD) or torque at a specified time period (e.g., force at 100 ms) during the first 200 or 300 ms of the MVC.

The assessment and reporting of these rapid muscle strength variables has markedly increased in the research literature within the last decade. These specific rapid strength variables have reached the point where they are routinely used in research by an increasing number of scientists across a range of human

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movement disciplines (e.g. sport performance, aging, disease, growth and development etc.; Maffiuletti et al., 2016). The recent increased interest and utilization of these measures is likely a result of increased widespread access to dynamometers of various forms, combined with the demonstrated usefulness of these variables to identify, discriminate, and predict functional outcomes across a broad range of human movement conditions (Thompson et al., 2013; Palmer et al., 2015; Gerstner et al., 2017; Thompson et al., 2017).

While the mathematical calculation of these digital torque signal-derived variables is relatively straightforward, less attention has been given to the treatment of the signal that occurs prior to the calculation of the variables. The signal derived from the dynamometer is typically conditioned to enhance its suitability for subsequent data extraction/analyses. Filters are commonly applied to the signal to improve its condition, or in other words, to reduce the unwanted noise from the signal. The optimal filtering procedure for the processing of the dynamometer-based isometric signals has not yet been precisely determined and recommendations are lacking. As a result, the literature has applied a wide variety and range of filter cutoff frequencies to condition MVC signals. For example, only a small sampling of the literature reveals that low-pass cutoff filters have been applied at frequencies of 3 (Morcelli et al., 2016), 5 (Mirkov et al., 2004), 10 (Conchola et al., 2013; Conchola et al., 2015), 15 (Aagaard et al., 2002; Barry et al., 2005), 20 (Bento et al., 2010; Jenkins et al., 2016; Thompson et al., 2018), 50 (Del Balso and Cafarelli, 2007; Gerstner et al., 2017), and 160 Hz (Tillin et al., 2012) as well as notch filtered at 100 Hz and 200 Hz (Tillin et al., 2010; Tillin et al., 2012). Notably, the majority of the studies appear to have applied the low-pass cutoff filter between the 10 Hz–20 Hz range, which is a rather low cutoff frequency.

The filter applied to the signal may be of considerable consequence to the output data, because a low filter cutoff frequency can lead to signal distortion (Winter, 2009), and therefore alter the data derived from the signal. However, a high filter cutoff may allow too much noise to pass (Winter, 2009) which could also alter the output data. Thus, a compromise must be made between the two filtering extremes (Winter, 2009). In regards to the torque-time parameters from the MVC curve, these filtering effects are likely to be more pronounced for the initial phase of the curve because the signal tends to be more distorted at the point of deflection from baseline, or in other words, as the filter transitions from the baseline into the rising signal. Thus, heavier filtering is likely to influence the early rapid torque phase to a higher degree than the maximum torque. Because of this filter-induced distortion of the curve, some authors have recommended applying minimal filtering to the signal, with a stipulation that if filtering is unavoidable, the highest possible cut-off frequency should be used (Maffiuletti et al., 2016). However, the specific threshold frequency at which the low-pass cut-off should be applied in order to optimally balance the filter distortion-to-noise tradeoff is unknown for the integrity of force- or torque-time parameters. This is especially relevant to the field because many investigators must, out of practical necessity, work with dynamometers that produce somewhat greater noise levels than the custom load cell-based setups that have been advocated for when performing these tests.

Also along these lines, the sampling rate (SR) of the MVC signal has also varied widely within the application of assessing these isometric MVC time-dependent variables. For instance, the SR has been reported at 100 (Ikemoto et al., 2004; Osawa et al., 2018), 200 (Mirkov et al., 2004), 500 (Quinlan et al., 2018), 1000 (Aagaard et al., 2002; Bento et al., 2010), and 2000 Hz (Tillin et al., 2010; Thompson et al., 2013, 2013). Although some authors have recommended SRs of at least 1000 Hz (Maffiuletti et al., 2016), data is limited which compares the degree to which SR vari-

ation may impact the torque-time values across a range of SRs, and to what extent a SR below 1000 Hz may possibly skew these values.

The high degree of inconsistency in the literature of these signal processing procedures may dilute across study comparative and replicable efficacy and is a product of limited and/or vague recommendations for these procedures. Therefore, the purpose of this investigation was to examine the effects of filtering and SR on torque-time parameters across a wide range of conditions using a traditional isokinetic commercial dynamometer in order to provide specific recommendations for future investigators when using these applications.

2. Methods

2.1. Subjects

Twenty-three recreationally active, non-resistance trained men between the ages of 21 and 29 years (mean \pm SD: age = 25.1 \pm 3.0 years; body mass = 88.1 \pm 21.5 kg; height 178.8 \pm 7.7 cm) completed this investigation. This study was approved by the university's Institutional Review Board for human subjects research and all participants completed a health history questionnaire and signed a written informed consent prior to any testing. Eligibility criteria required subjects to be free of any current neuromuscular diseases and have no musculoskeletal injuries of the knee or hip of their right leg within one year of the study.

2.2. Procedures

Subjects reported to the laboratory on two occasions, separated by two – four days. The first visit entailed completing the paperwork and a formal familiarization of the testing protocol. The second visit was the experimental trial. Isometric MVCs were performed on the right leg using a calibrated Biodex System 4 dynamometer (Biodex Medical Systems Inc., Shirley, NY). Prior to the MVCs, subjects performed a five minute warm-up on a cycle ergometer at a self-selected low-intensity workload (50% of perceived maximum effort). Subjects were seated on the dynamometer with restraining straps placed over the trunk, pelvis, and thigh and with the input axis of the dynamometer aligned with the axis of rotation of the knee joint. Subjects then performed three sub-maximal isokinetic knee extension and flexion repetitions at 60°·s⁻¹ at approximately 75% of their perceived maximum effort.

Subjects performed three MVCs of the knee extensors with one minute of rest between each MVC. For all MVCs, subjects were instructed to “push as hard and fast as possible” for a total of four seconds and strong verbal encouragement was provided throughout the contraction.

2.3. Signal processing

The raw torque signal (V) was sampled at 2000 Hz with a Biopac data acquisition system (MP150WSW, Biopac System Inc., Santa Barbara, CA) and processed off-line with custom written software (LabVIEW 2016, National Instruments, Austin, TX). The voltage signal was scaled to units (torque; Nm) using a regression formula derived from an “in house” calibration, and then filtered with a fourth-order zero-lag Butterworth filter at low-pass frequencies of 5, 10, 20, 50, 100 and 150 Hz as well as notch filtered at 100 Hz and 200 Hz. Also, in order to examine the influence of SR on the torque – time variables, the 150 Hz low-pass filtered signal at 2000 Hz was subsequently downsampled to yield signals with SRs of 100, 500 and 1000 Hz. Outcome measures included maximum and rapid torque characteristics for each signal processing

condition. Specifically, peak torque (PT) was calculated as the highest 500 ms epoch during the torque-time tracing, and RTD as the linear slope of the ascending portion of the torque-time signal at 50 (RTD50) and 200 (RTD200) ms from onset. Peak RTD (RTDPEAK) was determined as the highest value of the first derivative of the torque signal between onset and PT (Thompson et al., 2014). These RTD variables represent early, late and maximum RTD parameters and have been reported widely in the literature (Gerstner et al., 2017; Palmer et al., 2017; Thompson et al., 2018). The onset of torque was determined as the point where the torque signal reached 1 Nm above baseline. This automated threshold was used to ensure the same onset threshold was being selected across all signal processing conditions (e.g., to remove any variability that may be present with a manual onset technique) and the very low threshold allowed the early portion of the MVC signal to be captured in the RTD output parameters. MVCs which demonstrated a signal deviation from baseline were discarded. This was evaluated by computing the baseline slope of the 200 ms prior to the onset and

discarding MVCs with a slope value exceeding $2.5 \text{ Nm}\cdot\text{s}^{-1}$ (the mean slope value for all MVCs in the study was $0.17 \text{ Nm}\cdot\text{s}^{-1}$). The final data set included 49 MVCs from the 23 subjects.

2.4. Statistical analyses

Torque – time variable comparisons for the different signal conditions used percentage differences to determine if the signals were the same, which is a procedure used in previous work comparing force signal filtering variations on force – time variables (Street et al., 2001; Dos'Santos et al., 2018). Two signals were considered to be the same if they were within $\pm 2\%$ of each other, which is a slightly modified, and more conservative threshold from previous studies (they used 1%). Null-hypothesis significance testing (i.e., *P* values) was not used as a statistical technique in this study. The primary reason was that the nature of changes from signal processing procedures are atypical for, and uncondusive to, these conventional statistical procedures because there is no

Table 1
Comparisons showing relative differences (%) for each of the filter conditions for the peak, 50 and 200 rate of torque development (RTD) variables.

RTDPEAK	5	10	20	50	100	150	Notch
5	–	22.3	28.7	30.7	34.4	37.9	73.4
10		–	8.2	10.8	15.5	20.1	65.8
20			–	2.8	7.9	12.9	62.7
50				–	5.3	10.4	61.6
100					–	5.4	59.5
150						–	57.2
Notch							–
RTD50	5	10	20	50	100	150	Notch
5	–	18.8	–18.4	–19.0	–15.8	–14.2	–1.4
10		–	–45.8	–46.5	–42.6	–40.6	–24.8
20			–	–0.5	2.2	3.6	14.4
50				–	2.6	4	14.8
100					–	1.4	12.5
150						–	11.2
Notch							–
RTD200	5	10	20	50	100	150	Notch
5	–	–0.41	1.1	1.3	1.2	1.3	1.1
10		–	1.5	1.7	1.6	1.7	1.5
20			–	0.19	0.05	0.23	0.01
50				–	–0.14	0.04	–0.17
100					–	0.18	–0.03
150						–	–0.21
Notch							–

Matrix header values indicate the low-pass cutoff frequency condition for filter conditions of 5, 10, 20, 50, 100, 150 Hz and the notch (100–200 Hz) filter. Note: positive values denote the higher cutoff frequency condition (e.g., lower filtering) is a greater RTD value than the lower cutoff filter in the comparison.

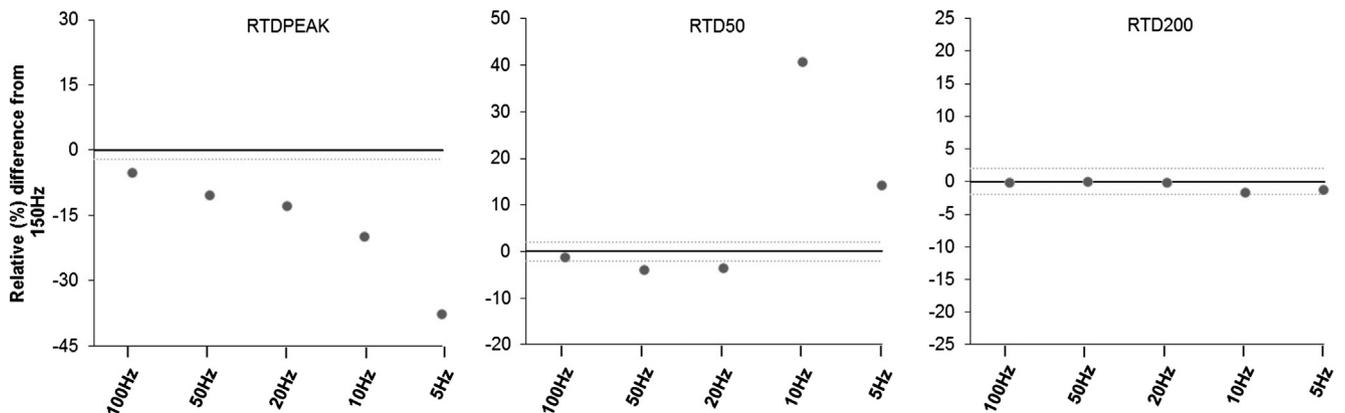


Fig. 1. Relative (%) differences of each low-pass filter cutoff condition compared to the 150 Hz condition for the rate of torque development (RTD) variables, including RTDPEAK, RTD50, and RTD200. Differences are from group means.

biological response in the signal processing effects, which largely lacks a random (error) component. Specifically, when the current data was initially examined in this manner, the changes of the values moved in the same direction in almost all MVCs as a result of applying any given filter and this effectually created a very small error term which provided a statistically significant scenario in every comparison, even when the means were different by < 0.5%. Thus, the present paper operates within a “practical purpose” context by using the percentage difference statistic to analyze the effects of signal processing on torque – time variable changes (Street et al., 2001). Reliability statistics were calculated for the first and second MVCs for 19 of the subjects for each of the RTD variables across all filter conditions. These statistics

included the intraclass correlation coefficient ($ICC_{3,1}$), standard error of measurement (SEM), and minimum detectable difference (MDD).

3. Results

There was no effect of filtering or SR on the PT variable (means = 248.57 Nm–248.61 Nm across all conditions).

The effects of filtering on the RTD variables are presented in Table 1 and Fig. 1. For RTDPEAK, when compared to 150 Hz, all filter frequencies showed a marked decrease (–5.4% for 100 Hz to –37.9% for 5 Hz; Fig. 1). For RTD50, when compared to 150 Hz, differences were noted for all the frequencies between 50 and 5 Hz

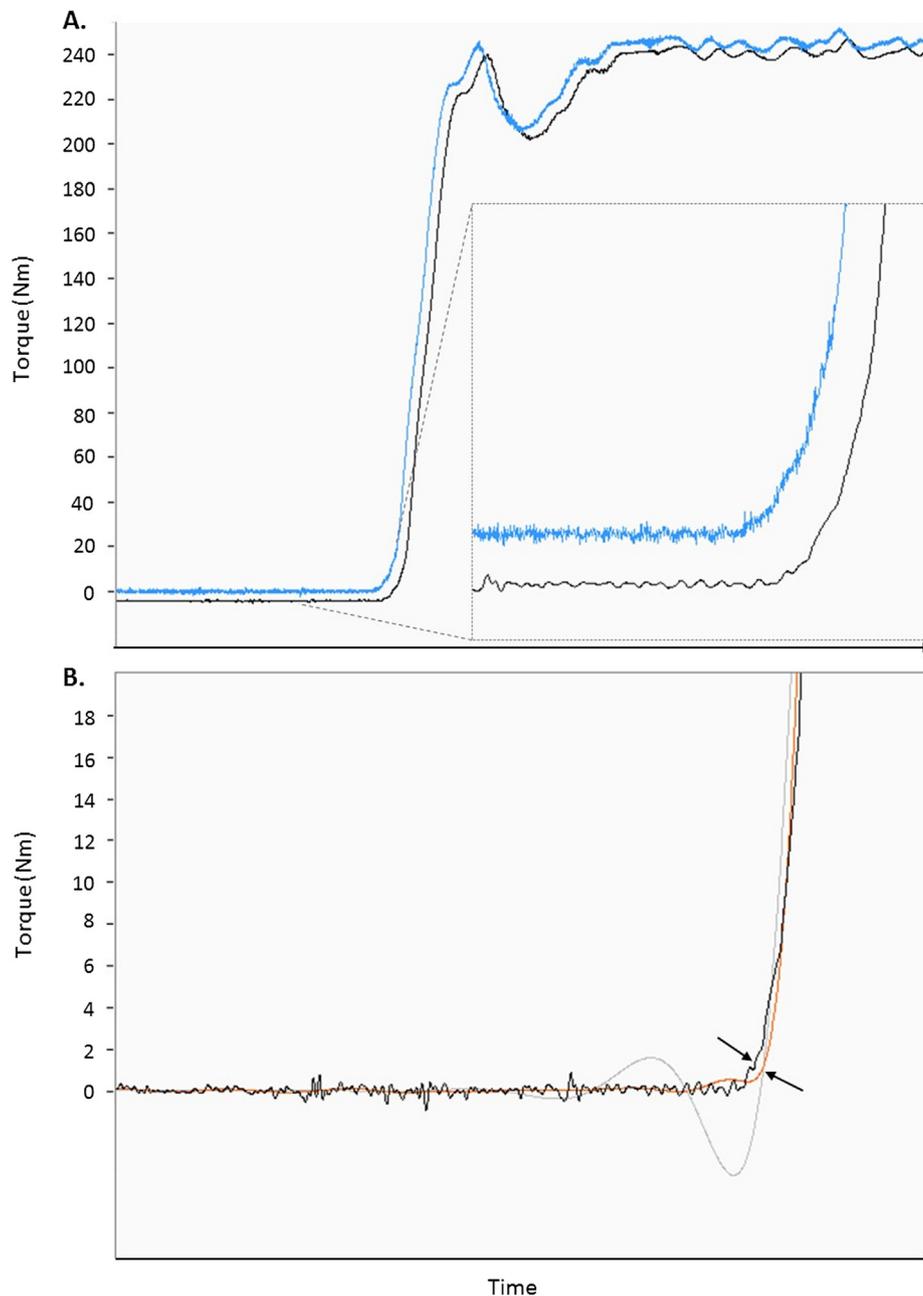


Fig. 2. Representative torque-time tracings showing the effects of filtering on the signals. (A) notch (blue) and 150 Hz low-pass filters (black). Note the difference in the unwanted (noise) signal characteristics between the notch and 150 Hz signals, particularly in the early ascending phase of the torque-time curve (signals are deliberately offset on the x-axis for visual clarity). (B) 150 (black), 10 (orange) and 5 (grey) Hz low-pass filtered signals. Note the effects of filtering on the early portion of the ascending phase of the torque-time curve. A large deformation of the signal is observed for the 5 Hz filtered signal (grey) and a discrepancy is also observed between the 150 Hz and 10 Hz filtered signals (arrows).

(−4.0% for 50 Hz – 40.5% for 10 Hz; Fig. 1). For RTD200, there were no differences noted for any of the filtering conditions (Fig. 1). Also, it was observed that the notch filter produced a signal that was not of sufficient quality to be used as a standard condition for which to compare the changes of all other filter conditions in the RTD variables (see Fig. 2), and so the values for the notch condition are not presented in the Fig. 1 data (for example the RTDPEAK value was $4962 \text{ Nm}\cdot\text{s}^{-1}$, which is $2839 \text{ Nm}\cdot\text{s}^{-1}$ higher than the 150 Hz value of $2123 \text{ Nm}\cdot\text{s}^{-1}$; a result of noise within the notch filtered signal). However, these comparison data for the notch filter are available in Table 1. Fig. 3 illustrates the effect of the filtering conditions on the power spectral density curves for the same MVC. Reliability statistics for the RTD variables for each condition are presented in Table 2. These statistics showed that increased filtering had a more substantial effect on the reliability for the RTDPEAK variable, whereas reliability was high and unaltered for the RTD200 variable for all signal filter conditions.

The effects of SR on the RTD variables are presented in Fig. 4. Substantial differences from 2000 Hz were noted for the 100 Hz condition for the RTDPEAK and RTD50 variables. There were no other differences among the 2000 Hz, 1000 Hz, and 500 Hz conditions for RTDPEAK and RTD50, or for the RTD200 variable.

4. Discussion

The present investigation showed that low-pass filter frequencies, and to a lesser extent, SR, can have an impact on the early

phase of the torque-time curve and the associated values derived from this portion of the curve.

Low-pass filtering had a more profound effect on the RTDPEAK and RTD50 (early) variables compared to the RTD200 (later) variable. For RTDPEAK, using 150 Hz as a reference signal, differences were noted for all the filter conditions from 100 Hz to 5 Hz with the larger differences being shown at the lower filter frequencies. For example, the low-pass filter altered RTDPEAK by as much as 38% (comparing 5 Hz vs. 150 Hz cutoffs) and filtering the signal at 10 Hz (a commonly used filter in torque – time analyses) reduced the RTDPEAK variable by a substantial 20% (Fig. 1). It should be noted that even the 100 Hz filter yielded a 5.4% lower value when compared to the 150 Hz filter, which is well beyond the 2% error mark that was set as the point where the signal could no longer be considered the same. For RTD50, differences were observed when compared to the 150 Hz condition for all filters between 50 Hz and 5 Hz from −4% to −40.5%. In particular, very large differences were found for the 10 Hz and 5 Hz filters. The reason for these discrepancies is the filter-induced deformation of the signal, which is more pronounced in the early portion of the ascending phase of the curve where the baseline converges with the rising signal (see Fig. 2). Interestingly, there were no marked differences in the RTD200 values across any of the filter conditions. These findings are generally in agreement with those of Dos'Santos et al. (2018) who recently compared low-pass filtering conditions for the isometric midhigh pull. A close inspection of their data shows that a 2.7% difference was observed between the 100 Hz

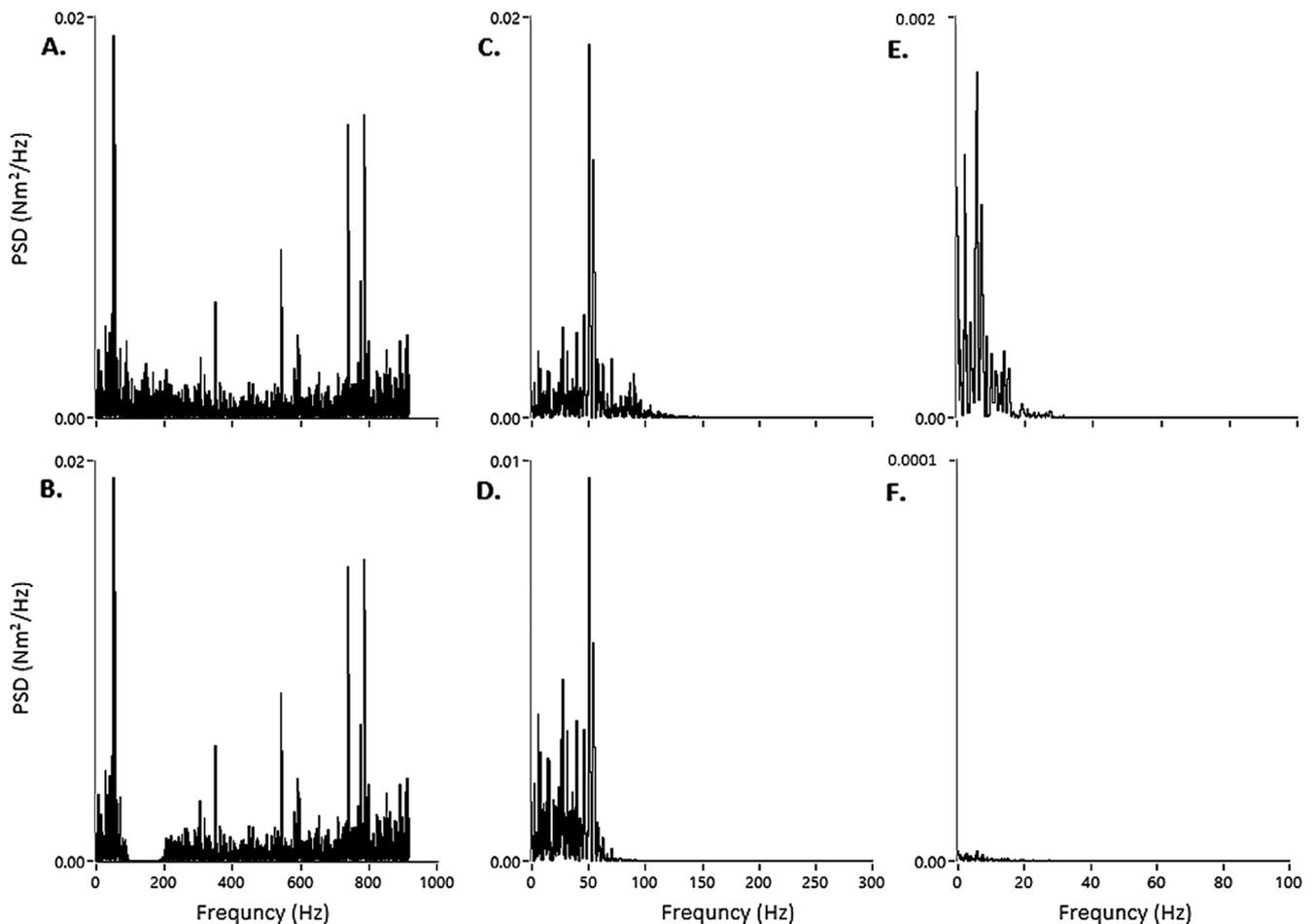


Fig. 3. Representative power spectral density (PSD) curves for the same MVC for the (A) raw unfiltered signal, (B) notch filter between 100 Hz and 200 Hz, and low-pass cutoff filters at (C) 150 Hz, (D) 100 Hz, (E) 50 Hz, and (F) 20 Hz. Note, the 10 Hz and 5 Hz filter conditions were not included in the illustration due to the very low signal visibility resulting from the heavy filtering at these conditions.

Table 2
Reliability statistics for the rate of torque development (RTD) variables for each filter condition.

Variable/filter cutoff	Reliability statistic		
	ICC _{3,1}	SEM	MDD
<i>RTDPEAK</i>			
5	0.93	85.72	237.59
10	0.91	154.46	428.13
20	0.88	190.08	526.87
50	0.85	210.39	583.16
100	0.83	219.67	608.90
150	0.81	234.27	649.36
Notch	0.10	872.74	2419.10
Raw	0	928.01	2572.31
<i>RTD50</i>			
5	0.93	60.88	168.75
10	0.93	105.88	293.48
20	0.77	206.22	571.60
50	0.79	167.66	464.72
100	0.80	170.95	473.86
150	0.80	163.16	452.26
Notch	0.84	157.06	435.36
Raw	0.81	174.36	483.30
<i>RTD200</i>			
5	0.94	65.56	181.73
10	0.93	70.66	195.85
20	0.93	72.51	200.99
50	0.93	71.63	198.55
100	0.93	74.09	205.36
150	0.93	70.20	194.59
Notch	0.93	69.71	193.21
Raw	0.94	67.26	186.40

ICC_{3,1} = intraclass correlation coefficient, model 3,1; SEM = standard error of measurement; MDD = minimum detectable difference. Raw = unfiltered signal; Notch = notch filtered between 100 Hz and 200 Hz; 5, 10, 20, 50, 100, 150 = low-pass cutoff frequency; RTDPEAK, RTD50 and RTD200 = rate of torque development at peak, 50, or 200 ms from onset, respectively.

and 10 Hz filter conditions for the force at 50 ms variable, but only a 0.7% difference existed for the force at 200 ms variable. The likely reason for this is that the more robust filtering induces a propor-

tionally greater signal distortion at the point where the baseline signal converges with the rising MVC curve, which would affect the earliest phases of the MVC curve more than the later time phases (see Fig. 2B for an illustration). Thus, the effect of signal filtering on the torque – time variables appears disproportionately impactful to the early (≤ 50 ms) phase of the curve. Studies that investigate rapid torque variables in the early phase (including RTDPEAK) should consider applying a low-pass filter at no lower than 150 Hz to avoid alterations in the signal and skewed parameters. When the measure of interest involves analyzing later phases (e.g., ≥ 200 ms) of the MVC curve, the filter applied is of little consequence, although filters of ≥ 20 Hz may still be recommended (Fig. 1).

The type of instrumentation used to produce an isometric MVC signal may also influence the ideal filtering method to be used. For example, the present study used a commercial dynamometer (Biodex) as opposed to a force plate or other type of linear strain gauge instrument (e.g., load cell). The latter may exhibit lower noise levels versus commercial dynamometers (Maffiuletti et al., 2016), and consequently, may allow for higher low-pass filtering thresholds (or notch filtering, which was insufficient when using the current instrument) as a means to preserve the original signal integrity while still producing a high quality signal for accurate calculation of the force- or torque-time variables. However, many research, clinical, or athletic settings are not suited for (or capable of attaining) custom isometric testing devices with low noise load cell instrumentation. The present work shows that an isometric MVC signal from a commercial dynamometer that is low-pass filtered at 150 Hz produces a quality signal for torque – time variable analyses that retains the key characteristics inherent in the signal and does not deform the signal to the degree of low-pass filters at lower frequencies. However, regardless of the instrument used to produce the force- or torque-time signal, filtering at lower frequencies can still alter the signal and skew the analyses, because the effect of the filter on the signal deformity is still present independently of the noise level of the signal. The filter-induced deformity that predominately impacts the early phase of the rising signal

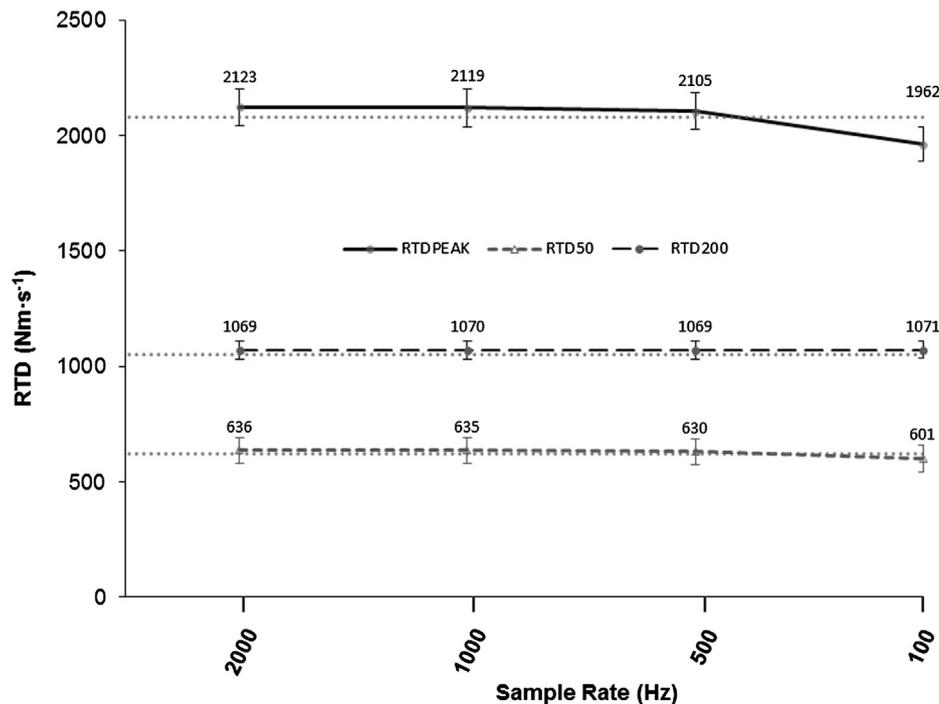


Fig. 4. Peak rate of torque development (RTDPEAK) and RTD at 50 and 200 ms (RTD50 and RTD200) values at sample rates of 2000 Hz, 1000 Hz, 500 Hz, and 100 Hz. Values are means \pm standard error of the mean. The dotted grey line denotes the point where a 2% change would be from the 2000 Hz condition values.

becomes more severe as the low-pass filtering becomes more intensive.

The SR was less influential on the torque – time curve variables such that notable differences were only observed for the 100 Hz condition when compared to 2000 Hz for the RTDPEAK and RTD50 variables. These differences were most pronounced for the RTDPEAK variable which showed a reduction of 7.6% from 2000 Hz to 100 Hz. Sample rates comparing 500 Hz and 2000 Hz showed only minor differences for both RTDPEAK (0.8%) and RTD50 (0.9%). Other than these instances, the values were nearly identical for the RTD200 variable across all SR conditions, and between the 2000 Hz and 1000 Hz conditions. Thus, a SR of 1000 Hz or above is recommended, although, if necessary, a SR as low as 500 Hz would likely be sufficient for these variables due to the very small error noted. Also, this data reveals there appears to be no improvement in RTD accuracy by sampling at 2000 Hz versus 1000 Hz as the values were nearly identical. Thus, for the sole purpose of assessing rapid torque or force variables from an MVC, 1000 Hz appears to be entirely sufficient, however, higher rates may be required if other measures are being collected that may warrant an increased SR > 1000 Hz (e.g., electromyography). Finally, these data showed that neither filtering nor SR changes the PT variable across any of the conditions examined (5 Hz – 150 Hz and 100 Hz – 2000 Hz, respectively).

The reliability statistics reported in the current study showed a large degree of improvement with increased filtering for the RTDPEAK variable (Table 2). For example, the ICC was 0.10 for this variable using the notch filter but increased substantially to 0.81 when filtered at 150 Hz. This is because of the unique quality of this variable as computed using a derivative function. The derivative of the signal is highly sensitive to fluctuations in the curve. Thus, a threshold level of signal filtering is required to yield a curve smooth enough to prevent large spurious spikes in the derivative signal. These results seem to show that the 150 Hz filter was adequate at smoothing the signal sufficiently to produce an acceptable level of reliability for the RTDPEAK variable. The RTD50, and more especially the RTD200 variable, showed good to excellent reliability for most all filter conditions. Therefore, strictly for reliability purposes, if the RTDPEAK variable is not a variable to be included in a study's analysis, the filtering makes little difference on the reliability of the other RTD variables that have epochs of ≥ 50 ms. However, although filtering conditions did not have a large effect on reliability for the RTD50 and RTD200 variables, this does not indicate that the filtering effects did not affect the validity of these RTD variables (especially the case for RTD50; see Figs. 1 and 2).

In summary, the present study demonstrated that low-pass filtering can substantially influence the torque – time curve and the associated variables at the early phase (≤ 50 ms) of the curve. There was practically no effect of filtering on the later (200 ms) rapid torque and PT variables. Sample rate also had an effect on the early rapid torque variables, but marked effects were only found when the sample rate was as low as 100 Hz. Based on these findings, the following are recommendations for signal processing of isometric MVC's derived from a commercial isokinetic dynamometer:

- (1) When rapid torque – time parameters are assessed from isometric MVCs that include time epochs within the first ~ 50 ms or use the peak derivative for maximum RTD, it is recommended that a low-pass filter with a 150 Hz cutoff is used to avoid signal distortion and/or skewed values. However, higher (>150 Hz) low-pass frequencies, or notch filters, may be warranted if the signal exhibits very low noise.
- (2) If later rapid torque variables (≥ 200 ms) are the only variables of interest, a low-pass cutoff of ≥ 20 Hz may most

completely eliminate error, although lower cutoffs may be used if necessary with minimal affect on the variable.

- (3) Sampling rates of at least 1000 Hz are ideally recommended for the most accurate assessment of early (≤ 50 ms) or maximum (RTDPEAK) rapid force or torque variables, although if necessary, a sample rate as low as 500 Hz may provide reasonably accurate values (within 1% error). For later variables (≥ 200 ms), sampling rates of ≥ 100 can provide highly accurate values.
- (4) If PT is the only variable assessed, the filter or sample rate is not influential on the PT value within the parameters of the current study, and thus, low-pass filters ≥ 5 Hz or sample rates ≥ 100 Hz can be recommended.

Conflict of interest

The author declares no conflicts of interest.

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