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Time to stabilization in single leg drop jump landings: An examination of calculation methods and assessment of differences in sample rate, filter settings and trial length on outcome values

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ABSTRACT

Time to stabilization (TTS) is the time it takes for an individual to return to a baseline or stable state following a jump or hop landing. A large variety exists in methods to calculate the TTS. These methods can be described based on four aspects: (1) the input signal used (vertical, anteroposterior, or mediolateral ground reaction force) (2) signal processing (smoothed by sequential averaging, a moving root-mean-square window, or fitting an unbounded third order polynomial), (3) the stable state (threshold), and (4) the definition of when the (processed) signal is considered stable. Furthermore, differences exist with regard to the sample rate, filter settings and trial length.

Twenty-five healthy volunteers performed ten 'single leg drop jump landing' trials. For each trial, TTS was calculated according to 18 previously reported methods. Additionally, the effects of sample rate (1000, 500, 200 and 100 samples/s), filter settings (no filter, 40, 15 and 10 Hz), and trial length (20, 14, 10, 7, 5 and 3 s) were assessed.

The TTS values varied considerably across the calculation methods. The maximum effect of alterations in the processing settings, averaged over calculation methods, were 2.8% (SD 3.3%) for sample rate, 8.8% (SD 7.7%) for filter settings, and 100.5% (SD 100.9%) for trial length. Differences in TTS calculation methods are affected differently by sample rate, filter settings and trial length. The effects of differences in sample rate and filter settings are generally small, while trial length has a large effect on TTS values.

1. Introduction

Dynamic testing of postural stabilization in sports, rehabilitation and orthopaedic medicine is receiving increasing interest, since dynamic tests are more demanding and sport-specific compared to static postural stability [1,2]. The most commonly applied test is the single leg jump or hop landing, which typically involves a forward and upward propulsion of the body by having subjects jump either from a box [3–5] or to a certain height [6–13], land upon a force plate on one foot, and stabilize as quickly as possible. One of the outcome measures to quantify performance on such a test is the 'time to stabilization' (TTS). The TTS is the time it takes for a subject to return to a baseline or stable state following a jump or hop. A longer TTS indicates more difficulty controlling posture at landing and might indicate impaired neuromuscular control [6–13].

A number of studies differentiated between participants, tasks or interventions using the TTS, examining the effect of chronic ankle instability (CAI) [7,14], functional ankle instability (FAI) [5,6,9–11,13,15], anterior cruciate ligament (ACL) deficiency and/or reconstruction [16,17], jumping distance [18], jumping direction [8], fatigue [1,3,19], ankle brace [1], injury prevention programme [4], neuromuscular training [20], stochastic resonance stimulation [21] and plyometric exercises [22].

Recently Liu et al. [23] examined the sensitivity and specificity of several dynamic postural stability measures with regard to ankle

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instability. None of the six calculation methods tested [16,24] was successful in detecting ankle instability. Furthermore, Wikstrom et al. [5] concluded that a large variety exists in TTS values between studies and that a consistent basis for comparison is lacking.

A TTS calculation method can be described based on four aspects: (1) the input signal (2) signal processing, (3) the stable state (threshold), and (4) the definition of when the (processed) signal is considered stable. The variance in outcome values may be due to differences between the TTS calculation methods used in the various studies. Input signals have varied across the vertical (V), anteroposterior (AP), and mediolateral (ML) ground reaction forces, which have been smoothed by sequential averaging [16], fitting an unbounded third order polynomial [24] or a moving root-mean-square window [25]. Furthermore, differences between studies exist with regard to the sample rate, filter settings and trial length.

Therefore, the aims of the current study were (1) to examine the effect of the calculation methods that have been used to date on TTS values; and (2) to quantify the effect of differences in sample rate, filter settings and trial length on TTS values.

2. Methods

2.1. Participants

A convenience sample of twenty-five healthy volunteers was recruited (20 men, 5 women; mean (range); age 28.6 (20–53) years; height 183.3 (163–197) cm; body weight 76.9 (59–96) kg). All subjects were currently free from lower extremity injury, central nervous system injury, and any disorder that might affect neuromuscular control. Written informed consent was obtained once the purpose, nature and potential risks had been explained. The study was performed according to the Declaration of Helsinki and approved by the Human Ethics Committee of the Faculty of Human Movement Sciences of the VU University in Amsterdam.

2.2. Data collection

Ground reaction forces (GRF) were recorded at 1000 samples/s by a 60 by 40 cm force plate (type 9218B, Kistler Instrument Corp., Winterthur, Switzerland), which was mounted flush with the laboratory floor. The registered data consisted of GRF's in vertical (V), anteroposterior (AP) and mediolateral (ML) directions.

Before the actual testing commenced, participants were asked to perform a few practice jumps in order to select the leg they felt most comfortable landing upon. Each participant was then asked to perform ten valid 'single leg drop jump landing' trials on their preferred leg, after hopping from a box of 30 cm height, positioned 5 cm posterior to the force plate. Participants were instructed to take off standing on a single leg, land on the same leg and stabilize as quickly as possible, balance for 20 s with their hands on the hips, while keeping all other movement to a minimum. No instructions with regard to jump height were given. All trials were performed on bare feet. A trial was considered invalid, if a participant displaced his/her standing leg, touched the floor with the contralateral leg or if arm movement was used to regain balance.

2.3. Identification of TTS calculation methods

A systematic search of the literature led to the inclusion of 29 studies (details on the selection process, participant and task characteristics, and associated TTS values (±SD) are presented in the supplementary data). Table 1 shows the eighteen identified calculation methods. Sixteen of these methods can be described based on four aspects: (1) the input signal used (2) signal processing (3) determination of the threshold (indicating the signal level at which the signal is considered stable), and (4) definition of which intersection between the (processed) signal and the threshold determines TTS.

(1) The input signal used to calculate TTS consisted of V, AP or ML GRF's.
(2) The signal processing (smoothing) of the input varied from no processing, i.e. using the '*raw*' GRF signal (RAW) [3,5,16,22,23,26–29], *sequential averaging* (SA), by adding one data point at a time, and calculating a new average after each added point [1,5,7,8,14,16,20,23,26,27,30], fitting an unbounded '*third order polynomial*' (TOP) starting at the peak GRF, using the following function: $f(x) = a_0 + a_1x + a_2x^2 + a_3x^3$, where

Table 1
Identified calculation methods.

Method	Processed signal	Threshold	Definition	References
VRAW1	None	Body weight ± 5%	Signal to remain within threshold	[3,5,16,22,23,26–28]
VRAW2	None	Body weight ± 5%	Signal to remain within threshold for 1 s	[29]
VSA1	Sequential average	Overall series mean ± 0.25 SD	Signal to remain within threshold	[8,16,20,23,30]
VTOP1	Third order polynomial	Minimal range (10–15 s or 15–20 s window)	Signal to threshold	[5]
APRAW3	None	Average range of variation (last 2 s) ± 5%	Signal to threshold	[3]
APSA1	Sequential average	Overall series mean ± 0.25 SD	signal to remain within threshold	[1,5,7,8,16,20,23,26,27,30]
APTOP1	Third order polynomial	Minimal range (10–15 s or 15–20 s window)	Signal to threshold	[5,6,9,15,19,23,24]
APTOP2a	Third order polynomial	Average range of variation (10–20 s window) + 3 SD[a]	Signal to threshold	[10,11,21]
APTOP2b	Third order polynomial	Average range of variation (8–9 s window) + 3 SD[a]	Signal to threshold	[4]
APRMS	RMS window (250 ms)	Minimal range (10–15 s or 15–20 s window)	Signal to remain within threshold for 0.5 s	[25]
MLRAW3	None	Average range of variation (last 2 s) ± 5%	Signal to threshold	[3]
MLSA1	Sequential average	Overall series mean ± 0.25 SD	Signal to remain within threshold	[1,5,7,8,16,20,23,26,27,30]
MLTOP1	Third order polynomial	Minimal range (10–15 s or 15–20 s window)	Signal to threshold	[5,6,9,15,19,23,24]
MLTOP2a	Third order polynomial	Average range of variation (10–20 s window) + 3 SD[a]	Signal to threshold	[10,11,21]
MLTOP2b	Third order polynomial	Average range of variation (8–9 s window) + 3 SD[a]	Signal to threshold	[4]
MLRMS	RMS window (500 ms)	minimal range (10–15 s or 15–20 s window)	Signal to remain within threshold for 0.5 s	[25]
RVSA2	Sequential average	Overall series mean (0–5 s) ± 0.25 SD	Signal to remain within threshold	[14]
RVTOP2a	Third order polynomial	Average range of variation (10–20 s window) + 3 SD[a]	Signal to threshold	[12,13,17–19]

An overview of the calculation methods identified, based on the processed signal, threshold and definition of TTS.
[a] Threshold averaged over *n* trials.

$a_3 \neq 0$ [4–6,9–13,15,17–19,21,23,24], or a moving '*root mean square*' window (RMS) [25].

(3) With regard to the 'threshold', an important distinction must be made. Most studies calculated a unique threshold for each individual trial, three studies however, based the determination of the threshold on the mean force fluctuation in *n* trials: '*average range of variation* (10–20 s *window*) + 3 *SD*' [10,11,21]. The four most commonly used constructs to calculate the thresholds are: '*body weight* ± 5%', which was only used for GRF in vertical direction [3,5,16,22,23,26–29], '*overall series mean* ± 0.25 *SD*', which calculates the mean (absolute) GRF per trial for the entire trial length in V, AP and ML directions [5,8,16,20,23,26,27,30], '*minimal range for a* 10–15 s *or* 15–20 s *window*', which calculates the range (maximum GRF–minimum GRF) for both time windows per trial and uses the smallest of the two as threshold [5,6,9,15,19,23–25], and '*average range of variation* (10–20 s *window*) + 3 *SD*', which calculates the average range and the associated SD within a participant [10–13,17,18,21].

(4) Two alternatives were used for the 'definition'. One being the time elapsed when the processed signal intersects the threshold for the first time ('*signal to threshold*') [1,3–7,9–13,15,17–19,21,23,24]. The second being the time elapsed when the processed signal intersects the threshold for the last time, after which it stayed within the threshold range ('*signal to remain within threshold*') [3,5,8,14,16,20,22,23,26–28,30]. Two studies modified the latter definition by stating that the processed signal should remain within the threshold for a limited time period only: 1 s [29] or 0.5 s [25].

With regard to the remaining two TTS calculation methods, TTS was not solely based on V, AP or ML GRF, but a resultant vector of TTS was constructed (RVTTS). First the TTS in AP and ML directions were to be calculated. Then, the RVTTS was established using the following function: $RVTTS = \sqrt{(TTSAP^2 + TTSML^2)}$.

2.4. Data processing

A custom MATLAB (The Mathworks, Natick, RI, USA) programme was written for all data processing. Raw data were cropped from time of impact (>10 N) to 20 s post-impact. Subsequently, the GRF's were divided by the participant's body weight, which was calculated as the average vertical GRF from 10 s to 20 s. To evaluate the effect of the differences in TTS calculation methods, for each trial, the TTS was calculated according to the identified methods (Table 1). All GRF signals for AP and ML were rectified, except for the sequential averaging methods.

Studies using the abovementioned calculation methods employed a range of sample rates (100–1000 samples/s), filter settings (no filter to 14 Hz low-pass cut-off frequency), and trial lengths (3–20 s) (see supplemental data for details). To identify the effects of these data acquisition and processing settings, we employed a range of values for these parameters. We used sample rates of 1000, 500, 200 and 100 samples/s. This was achieved by resampling of initial data (e.g. in order to resample 200 samples/s from 1000 samples/s, we discarded 4 out of every 5 samples, and kept the first out of every 5 samples). To examine the effect of filter settings, we employed no filtering, and a second order Butterworth bidirectional filter with cutoff filter frequencies of 40 Hz, 15 Hz, and 10 Hz. With regard to the trial length, we used trial lengths of 20 s, 14 s, 10 s, 7 s, 5 s and 3 s. However, if the threshold definition was based on a fixed time sequence (e.g. 10–15 s or 15–20 s; see Table 1 for details), trial length could not be shortened.

To identify possible interaction effects of sample rate, filter settings and trial length, we calculated the TTS for all possible combinations. Therefore, for each of 240 trials (24 subjects × 10 repetitions), for each of 18 calculation methods, TTS values were calculated for 4 sample rates × 4 filter settings × 6, 5, 3 or 1 trial length(s).

2.5. Data analysis

We calculated the mean outcome value and SD for each of the eighteen identified calculation methods (sample rate = 1000 - samples/s; filter setting = none; trial length = 20 s) as benchmark values, i.e. as reference values for calculated change in percentages.

After averaging over 10 repetitions per subject, we assessed effects of processing methods by applying, per TTS calculation method, a full factorial repeated measures ANOVA with sample rate (4 levels), filter settings (4 levels) and trial length (6 levels) as factors. Statistical significance was set at $p < 0.05$. Given the primary interest in overall effects and sheer number of tests,

Table 2
Time to stabilization outcome values and *p*-values for the effects of sample rate, filter settings and trial length.

	Outcome values		rm ANOVA				Interactions			
	Mean	SD	Model	sr	fs	tl	sr × fs	sr × tl	fs × tl	sr × fs × tl
VRAW1	2.75	4.42	4 × 4 × 6	0.102	0.004	0.007	0.003	0.129	0.052	0.125
VRAW2	1.02	0.61	4 × 4 × 6	0.355	0.000	0.704	0.004	0.658	0.479	0.477
VSA1	4.56	0.30	4 × 4 × 6	0.000	0.030	0.000	0.016	0.000	0.030	0.018
VTOP1	3.25	0.34	4 × 4 × 1	0.000	0.000		0.000			
APRAW3	0.51	0.24	4 × 4 × 6	0.000	0.000	0.000	0.000	0.000	0.567	0.513
APSA1	6.06	0.37	4 × 4 × 6	0.001	0.000	0.000	0.000	0.000	0.000	0.000
APTOP1	3.34	0.38	4 × 4 × 1	0.000	0.000		0.000			
APTOP2a	4.16	0.23	4 × 4 × 1	0.000	0.000		0.010			
APTOP2b	3.94	0.26	4 × 4 × 3	0.000	0.000	0.000	0.007	0.000	0.000	0.002
APRMS	1.29	0.60	4 × 4 × 1	0.000	0.000		0.000			
MLRAW3	0.11	0.07	4 × 4 × 6	0.000	0.000	0.000	0.109	0.000	0.043	0.677
MLSA1	1.34	0.58	4 × 4 × 6	0.538	0.000	0.000	0.000	0.029	0.002	0.673
MLTOP1	1.93	1.18	4 × 4 × 1	0.000	0.003		0.000			
MLTOP2a	3.53	1.12	4 × 4 × 1	0.000	0.000		0.008			
MLTOP2b	3.01	1.19	4 × 4 × 3	0.000	0.000	0.000	0.096	0.000	0.000	0.001
MLRMS	1.53	0.86	4 × 4 × 1	0.015	0.000		0.000			
RVSA2	2.48	0.14	4 × 4 × 5	0.019	0.000	0.000	0.000	0.000	0.432	0.541
RVTOP2a	5.43	0.82	4 × 4 × 1	0.000	0.000		0.006			

Mean TTS and SD; repeated measures ANOVA model (sr × fs × tl) and *p*-values for sample rate, filter settings and trial length. Calculation methods that employed threshold definitions based on a fixed trial length were excluded for the applicable trial lengths. sr, sample rate; fs, filter settings; tl, trial length.

no post hoc analyses were performed if significance was achieved. The magnitude of the effect of data processing settings on TTS values per calculation method was determined by comparing the largest TTS value with the smallest for each main effect and two-way interaction: $max\ effect\ (in\ \%) = ((max(TTS) \times 100)/(min(TTS))) - 100$.

3. Results

3.1. Calculation methods

One participant needed 32 attempts at the single leg drop jump landing in order to complete 10 valid trials. These 22 failed trials formed an outlier, hence this participant was excluded from further analysis. For the remaining 24 participants, the mean number (range) of invalid trials was 3.1 (0–6). Mean TTS values varied considerably between calculation methods, ranging from 0.11 s up to 6.06 s (Table 2). To understand these results, the underlying basis for the TTS calculation methods and outcome values is illustrated in Fig. 1. Calculation methods differ with respect to 'processed signals' (RAW, SA, TOP & RMS), 'thresholds' (particularly shown in Fig. 1d and g) and 'definitions' (compare VRAW1 and VRAW2 in Fig. 1a and b). The exact characteristics regarding the 'processed signals', 'thresholds', and 'definitions', as well as the exact acronym used for each calculation method, are presented in Table 1.

3.2. Data processing settings

Results showed a significant effect of sample rate (1000, 500, 200 or 100 samples/s) for 15 out of 18 calculation methods (Table 2). However, the magnitude of the effect was generally small (Fig. 2a), with a maximum effect range of 0.2–12% for all methods, except for MLRAW3 (>56%). This method had a very low mean TTS value of 0.11 s, hence small differences will lead to high relative differences. For most calculation methods the effect of sample rate on TTS declined when a filter was employed (Table 3).

The adjustments of filter settings (no filter, 40, 15 or 10 Hz) resulted in a significant effect on TTS values for all calculation methods (Table 2). The magnitude of the effect was generally small (Fig. 2b), though larger than for sample rate, with a maximum effect range of 0.7–37%, apart from MLRAW3 (>37%). The effect of filtering tended to decline when a smaller sample rate was employed (Table 3).

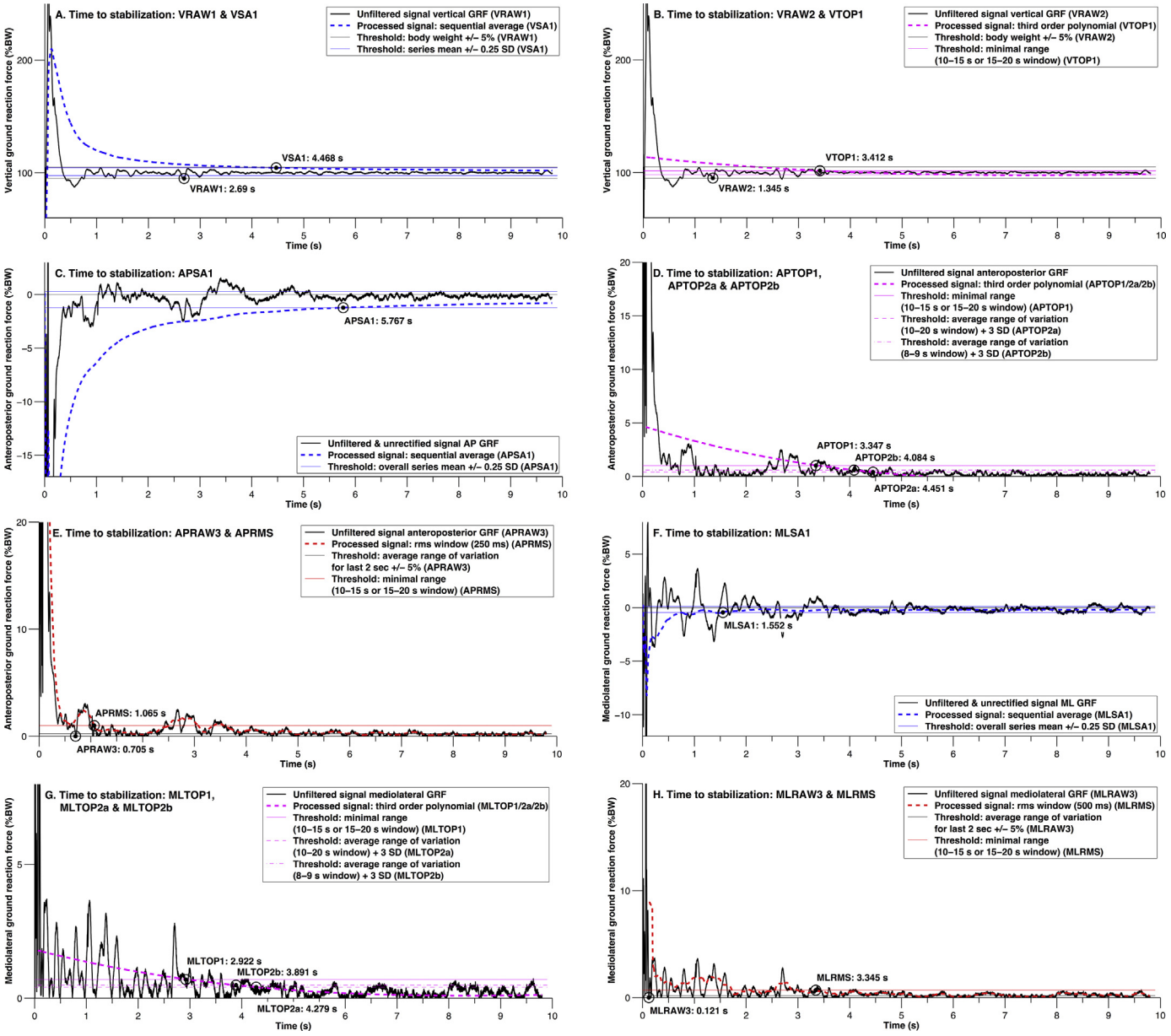

Fig. 1. (a–h) A graphical representation of the calculation of TTS based on the identified methods, for a typical single leg drop jump trial (participant 2, trial 8). Ground reaction forces (GRF) were recorded in three directions: Vertical (V) (a and b), anteroposterior (AP) (c–e) and mediolateral (ML) (f–h). All GRF signals for AP and ML were rectified, except for the sequential averaging (SA) methods (c and f). Sample rate: 1000 samples/s; filter settings: no filter; trial length: 20 s.

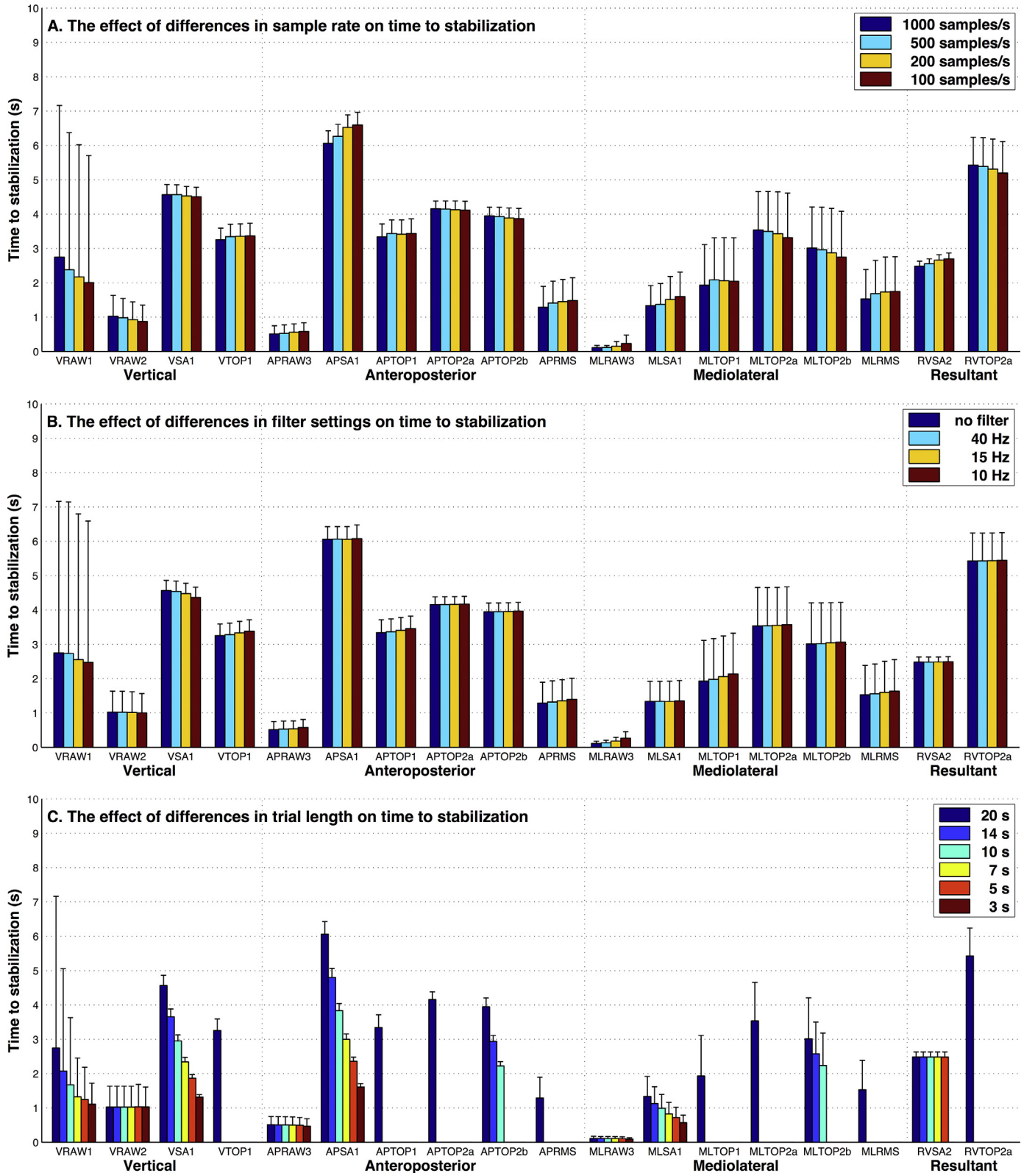

Fig. 2. (a–c) The effect of differences in sample rate (a), filter settings (b) and trial length (c) on the mean TTS for a group of 24 healthy subjects, calculated according to the eighteen identified methods. Threshold definitions based on a fixed trial length were excluded for the applicable trial lengths.

With regard to different trial lengths (20, 14, 10, 7, 5 and 3 s), eight calculation methods (VTOP1, APTOP1, APTOP2a, APRMS, MLTOP1, MLTOP2a, MLRMS & RVTOP2a) did not allow the adjustment to a trial length shorter than 20 s, two methods were limited to 10 s (APTOP2b & MLTOP2b), and one method was limited to 5 s (RVSA2) (Table 2). All analyses, except for VRAW2, showed significant effects of trial length on TTS values (Table 2), with shorter time series leading to shorter TTS values (Fig. 2c). The magnitude of the effect was large for six calculation methods with a maximum effect range of 28–285%. Alterations of sample rate and/or filter settings mostly lead to small differences in the effect of trial length, though one method (MLRAW3) was strongly affected (Table 3).

Table 3
Magnitude of effect of sample rate, filter settings and trial length on TTS outcome values.

	sr (max diff %)		fs (max diff %)		tl (max diff %)		
sr			1000 Hz	100 Hz	1000 Hz	100 Hz	1000 Hz
fs	none	10 Hz			none	none	10 Hz
tl	20 s	20 s	20 s	20 s			
VRAW1	10.9	1.5	36.9	22.0	147.5	128.4	112.7
VRAW2	2.2	2.3	17.3	12.2	0.8	0.7	1.0
VSA1	4.6	5.1	1.3	1.8	247.0	242.7	246.1
VTOP1	4.0	1.3	3.5	0.8			
APRAW3	12.4	5.6	13.7	7.2	9.5	11.6	9.2
APSA1	0.3	0.1	8.8	8.6	276.1	275.9	285.1
APTOP1	3.5	1.1	3.0	0.7			
APTOP2a	0.4	0.5	1.0	0.9			
APTOP2b	0.6	0.8	2.0	1.8	77.6	77.6	73.2
APRMS	8.0	2.2	14.7	8.6			
MLRAW3	137.4	56.3	108.6	37.3	18.4	57.2	3.3
MLSA1	1.4	1.3	19.6	19.7	135.1	138.0	119.8
MLTOP1	10.6	1.7	8.0	3.8			
MLTOP2a	1.0	1.0	6.5	6.5			
MLTOP2b	1.7	1.3	9.7	10.2	34.7	35.8	28.0
MLRMS	6.7	0.9	14.4	8.2			
RVSA2	0.3	0.2	8.5	8.4	0.0	0.0	0.0
RVTOP2a	0.4	0.5	4.4	4.3			

Magnitude of effect for sample rate, filter settings and trial length. Maximum difference (in %) = ((max(TTS) × 100)/(min(TTS))) − 100. Calculation methods that employed threshold definitions based on a fixed trial length were excluded for the applicable trial lengths. sr, sample rate; fs, filter settings; tl, trial length.

4. Discussion

Time to stabilization was established using a variety of calculation methods, which resulted in a large range of TTS values. These values were in turn affected by sample rate, filter settings and trial length. Differences in trial length had the largest effect on TTS values, with longer trial lengths leading to higher TTS values (up to 285%). In contrast, alterations of sample rate and filter settings had mostly minor, though significant, effects on TTS values (Fig. 2). Moreover, the effect of trial length was marginally influenced by variations in sample rate and filter settings (with the exception of MLRAW3) (Table 3). This suggests that especially trial length deserves consideration, when comparing TTS values between studies. This is important as trial length in particular differs across studies that have employed the same calculation methods (see supplementary data for details).

The TOP calculation methods fitted the original GRF data to a lesser extent than the other processed signals (Fig, 1b, d and g) and outcomes were also highly dependent on trial length; a longer time leads, by definition, to a more horizontal signal and thus a larger TTS. This questions the validity of these calculation methods, as it seems principally incorrect that when a stable position is maintained for a longer period, this would lead to a higher TTS value. In contrast, a moving RMS window (250 ms for APRMS and 500 ms for MLRMS) resembled the raw GRF data rather closely (Fig. 1e and h), hence a longer trial length will not affect the processed signal. However, in contrast to the SA and TOP that intersect the threshold only once, the RMS signal may intersect the threshold several times. Therefore, the associated definition requires the signal to remain within the threshold for at least 0.5 s [25].

Differences in methods to determine the threshold had a considerable effect on the TTS values as well (Fig. 1d, f and g). The general concept of TTS is that it assesses the ability of an individual to regain a stable position. Therefore, the establishment of most thresholds (of stable stance) is related to the variance of the GRF during a period at the end of a trial, when an individual can be considered to have achieved stable single leg stance. Thus, participants with a larger variance during the stable phase will have a higher threshold. Consequently, the processed signal will intersect the threshold earlier, lowering the TTS. One could argue this results in an underestimation of the TTS.

Most alterations of data processing settings yielded significant changes in the calculated TTS value (Table 2). However, alterations in sample rate, filter settings and/or trial length supposedly have a systematic effect, hence quantification of this effect seems necessary for adequate interpretation. The mean of the maximum difference (in %), averaged over all calculation methods except for MLRAW3, was 2.8% (SD 3.3%) for sample rate and 8.8% (SD 7.7%) for filter settings (Table 3). This suggests that filter settings are more important to consider than sample rate. Moreover, the trial length appeared to be the most important, with a mean maximum difference of 100.5% (SD 100.9%). Although in general the effects of sample rate and filter setting were of smaller magnitude, the calculation methods that use the raw GRF signal to establish TTS still yielded maximum differences above 10%. This was also true for the calculation method RMS with regard to filter setting effect.

Independent of calculation method, the length of the single leg drop jump landing procedure should be sufficiently long to be able to reach a stable position, otherwise the TTS values will be underestimated, which might be true for trial lengths of 3 and 5 s.

A possible limitation of the current study is that the landing protocol (i.e. step or jump) has a significant effect on TTS values as well [5]. Therefore, the present TTS results might not generalize to all jump/hop landings, since they are based on a specific drop jump landing protocol. Furthermore, some subjects, especially those with a large number of invalid trials, may have experienced some fatigue, and this may have affected TTS values. The same may hold for past lower extremity injuries. However, our comparisons of methods and processing settings were applied within a trial, instead of between trials. Therefore it is unlikely that either fatigue or past injuries biased our primary results.

In conclusion, important differences existed between TTS calculation methods, which in turn were affected differently by sample rate, filter settings and trial length. The effects of differences in sample rate and filter settings were generally small

(below 10%), while trial length had a large effect (up to over 200%) on TTS values.

Conflict of interest statement

None.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2014.08.018.

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