Influence of Speed and Step Frequency during Walking and Running on Motion Sensor Output

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ABSTRACT

ROWLANDS, A. V., M. R. STONE, and R. G. ESTON. Influence of Speed and Step Frequency during Walking and Running on Motion Sensor Output. *Med. Sci. Sports Exerc.*, Vol. 39, No. 4, pp. 716–727, 2007. **Purpose:** Studies have reported strong linear relationships between accelerometer output and walking/running speeds up to 10 km·h^{-1}. However, ActiGraph uniaxial accelerometer counts plateau at higher speeds. The aim of this study was to determine the relationships of triaxial accelerometry, uniaxial accelerometry, and pedometry with speed and step frequency (SF) across a range of walking and running speeds. **Methods:** Nine male runners wore two ActiGraph uniaxial accelerometers, two RT3 triaxial accelerometers (all set at a 1-s epoch), and two Yamax pedometers. Each participant walked for 60 s at 4 and 6 km·h^{-1}, ran for 60 s at 10, 12, 14, 16, and 18 km·h^{-1}, and ran for 30 s at 20, 22, 24, and 26 km·h^{-1}. Step frequency was recorded by a visual count. **Results:** ActiGraph counts peaked at 10 km·h^{-1} (2.5–3.0 Hz SF) and declined thereafter (r = 0.02, P > 0.05). After correction for frequency-dependent filtering, output plateaued at 10 km·h^{-1} but did not decline (r = 0.77, P < 0.05). Similarly, RT3 vertical counts plateaued at speeds > 10 km·h^{-1} (r = 0.86, P < 0.01). RT3 vector magnitude and anteroposterior and mediolateral counts maintained a linear relationship with speed (r > 0.96, P < 0.001). Step frequency assessed by pedometry compared well with actual step frequency up to 20 km·h^{-1} (approximately 3.5 Hz) but then underestimated actual steps (Yamax r = 0.97; ActiGraph pedometer r = 0.88, both P < 0.001). **Conclusion:** Increasing underestimation of activity by the ActiGraph as speed increases is related to frequency-dependent filtering and assessment of acceleration in the vertical plane only. RT3 vector magnitude was strongly related to speed, reflecting the predominance of horizontal acceleration at higher speeds. These results indicate that high-intensity activity is underestimated by the ActiGraph, even after correction for frequency-dependent filtering, but not by the RT3. Pedometer output is highly correlated with step frequency. **Key Words:** PEDOMETER, ACCELEROMETER, UNIAXIAL, TRIAXIAL, ACTIGRAPH, RT3

Continuing technological advances in physical activity measurement have contributed to increased development and use of various activity monitors (i.e., pedometers and accelerometers) for assessing physical activity in free-living conditions. These devices can be worn on the ankle, wrist, or trunk. However, trunk placement (usually the hip) is the most common site for placement (26). A pedometer is used predominately to assess steps taken during ambulatory activity (i.e., walking and running). An accelerometer measures accelerations and decelerations of movement. Current accelerometers are designed to detect acceleration in the vertical plane (uniaxial) or in up to three planes (triaxial–vertical, mediolateral, and anteroposterior).

Several studies have reported a strong linear relationship between accelerometer output and speed or energy cost of walking/running in children and adults (10,11,16,17,22,24). However, these studies typically only tested the devices at speeds up to approximately 10 km·h^{-1}. More recently, after testing at higher speeds, the validity of the ActiGraph uniaxial accelerometer (also known as the CSA, the MTI, and the WAM) has been shown to depend on speed. Brage et al. (5) examined ActiGraph output during walking (3–6 km·h^{-1}) and running (8–20 km·h^{-1}) in adults in laboratory and field conditions. Their results show that ActiGraph output (assessed in counts per minute) increased linearly (R^2 = 0.92, P < 0.001) with increasing speed up to 9 km·h^{-1} but then remained constant at approximately 10,000 counts per minute beyond this speed. Research in children has demonstrated similar findings, except that leveling off occurred at a lower ActiGraph output (approximately 8000 counts per minute) (6).

This leveling off of ActiGraph counts is indicative of frequency-dependent filtering (7), whereby the signal

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from the ActiGraph is weighted according to the frequency of movement, with frequencies higher or lower than 0.75 Hz being subject to decreasing weighting (25). The purpose of filtering is to reject accelerations unlikely to be generated by human movement. However, step frequency will generally be around 2.5 Hz at low speeds of running and will increase in a curvilinear manner with running speed (8). As running speed increases incrementally from 10 to 20 km·h^{-1}, the corresponding increments in step frequency are relatively small. However, as running speed is increased from 20 km·h^{-1} to maximum speed, the increases in step frequency are proportionately greater (8). Therefore, the effects of frequency-dependent filtering are likely to be particularly apparent at speeds > 20 km·h^{-1}, equivalent to a kilometer in 3 min, or a mile in just over 4.8 min. Although these speeds are unlikely to be maintained for minutes at a time by most people, accelerometers are capable of assessing activity using 1-s epochs. The use of short epochs is most likely when it is important to capture brief episodes of vigorous- or high-intensity activity. Therefore, it is important to investigate the capability of accelerometers, when set at these short epochs, to capture vigorous- and high-intensity activity.

Research suggests that the vertical displacement of the body does not change as the speed of running increases until sprinting speeds, when vertical displacement decreases (8). Conversely, horizontal displacement of the body is directly proportional to the rate of body movement during a stride (8). Uniaxial devices are normally designed to be worn with the orientation of the sensitive axis in the vertical plane. Therefore, as suggested by Brage and colleagues (5), the inability of uniaxial devices such as the ActiGraph to measure horizontal acceleration, which predominates at greater speeds, may contribute to the leveling off of counts also observed by others in the field (12,14). This would compound the effect of frequency-dependent filtering. In light of this, the question arises whether a triaxial device such as the RT3, which is programmed to assess movement in three planes (vertical, mediolateral, and anteroposterior) and to calculate a composite measure of accelerations in these planes, might be able to provide a more reliable and valid assessment of running speeds than uniaxial devices.

In addition, the performance of relatively cheap electronic pedometers at high speeds is not known. In conjunction with a measure of time, these can be used to provide a measure of step frequency. The Yamax SW-200 pedometer has been shown to provide a valid and reliable step count at walking speeds (3) and to have a linear relationship with oxygen consumption at speeds up to 10 km·h^{-1} in children (10), but, to our knowledge, it has not been tested at fast running speeds.

The aim of this study was to determine the relationships of the triaxial RT3 accelerometer, the ActiGraph uniaxial accelerometer, and the Yamax pedometer with speed and step frequency (SF) across a wide range of walking and running speeds.

METHOD

Procedure

Ten male trained short- and middle-distance runners (800–5000 m) were recruited from the university athletics club (age = 23.1 ± 3.4 yrs; height = 177.9 ± 5.6 cm; mass = 72.5 ± 8.1 kg). The institutional ethics committee granted approval, and all participants gave written informed consent. All participants were asked to complete two trials. Nine participants completed both trials 1 and 2, but trial 1 RT3 data for one participant were lost because of accelerometer failure.

Participants wore two RT3 accelerometers and two Yamax pedometers, one of each positioned above each hip, using the integral belt clips. Two ActiGraphs were worn on the elastic belt supplied, one positioned over each hip, oriented to assess accelerations in the vertical plane.

Each participant walked (constant ground contact) on a motor-driven treadmill (Woodway Slat Belt ELG55 Weiss, Weil Am Rhein, Germany) for 60 s at 4, 5, and 6 km·h^{-1}, ran (visible flight phase) for 60 s at 8, 10, 12, 14, 16, and 18 km·h^{-1}, and ran for 30 s at 20, 22, 24, and 26 km·h^{-1}. The time taken for 20 steps via a visual count (actual steps) was recorded twice at each speed to calculate step frequency. For each speed, step frequency was calculated as the mean of the two visual counts. The same researcher (M.S.) counted step frequency for all participants. A pilot study demonstrated that the mean coefficient of variation between step frequency assessed from a direct visual count and, later, video analysis, was 0.7% (range = 0.2–1.6%) across all speeds tested. Speeds were presented in a sequential order, with 1–5 min of rest between speeds as required. Participants returned on a separate occasion within 1 month, and the above protocol was repeated to determine test–retest reliability.

EQUIPMENT

RT3

The RT3 (Stayhealthy, Inc., Monrovia, CA) is sensitive along three orthogonal axes (x, y, and z), which represent vertical, anteroposterior, and mediolateral motion, respectively. A composite measure (resultant vector magnitude, vm) is calculated from $(x^2 + y^2 + z^2)^{0.5}$. The vector magnitude accounts for accelerations in all three planes and is the most common RT3 output measure reported in the literature. The RT3 has a dynamic range of 0.05–2.0g and is sensitive in the range 2–10 Hz. The exact relationship of the activity count to the acceleration (measured in meters per squared seconds or g, where $1g = 9.81$ m·s^{-2}) is not clear. The RT3 can be programmed to record data on a second-by-second or minute-by-minute basis (1- or 60-s epoch, respectively). Duration of data collection is very limited when 1-s epochs are used and/or when information from individual vectors is required. When a 1-s epoch is used, data can be collected for up to 3 h (**x**, **y**, and **z**

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vectors, and vm) or 9 h (vm only). When a 60-s epoch is used, data can be collected for up to 7 d (**x**, **y**, and **z** vectors, and vm) or 21 d (vm only). In the present study, a 1-s epoch was used, and data were collected along all three axes. Data were uploaded to the relevant software. To ensure that the data represented steady running, the first and last five data points were removed from each speed. Data (RT3vm, RT3x, RT3y, and RT3z) were expressed in counts per second.

ActiGraph

The ActiGraph accelerometer (GT1M, Fort Walton Beach, FL) is sensitive to activity along the vertical axis. Previous versions of the ActiGraph have been referred to as the CSA and the MTI. The ActiGraph has a dynamic range of $\pm 2.13g$ and is sensitive in the range 0.21–2.28 Hz. However, the frequency-dependent filtering of the ActiGraph means that movements are weighted to a different degree depending on the frequency of the movement, with only movements at 0.75 Hz being weighted at 1.0 (7). The ActiGraph can be programmed to record data in epochs between 1 s and 5 min or, when in raw data mode, at a rate of 30 Hz. When storing data in raw mode, the ActiGraph will collect data for 2 h 45 min. When a 1-s epoch is used, data can be collected for 5 d, which is considerably longer than when using a 1-s epoch with the RT3. The ActiGraph also has a pedometer function that allows simultaneous collection of step counts. In the present study, a 1-s epoch was used to collect accelerometer and step data. Data were uploaded to the relevant software. To ensure that the data represented steady running, the first and last five data points were removed from each speed. Accelerometer data (ActiGraph) were expressed in counts per second, and pedometer data (ActPed) were expressed in steps per minute.

Brage et al. (7) have developed an equation from a mechanical setup that corrects ActiGraph output, by converting counts per minute to acceleration, so that all values in the range 0.95–4.00 Hz are measured with the same weighting. ActiGraph counts were converted to counts per minute and were then entered into the following equation to remove the effect of frequency-dependent filtering (CorrACT):

$$\text{CorrACT } (\text{m·s}^{-2}) = 0.346 + \text{ActiGraph}/190.48 f^2 - 1848.54 f + 4794.97$$

where f is movement frequency (Hz), calculated from the visual count.

It should be noted that it is only possible to convert ActiGraph output to acceleration if the step frequency is known. The pedometer incorporated in the ActiGraph allows the simultaneous collection of step-frequency data; however, this function is designed for when the ActiGraph is set at 1-min epochs. It is possible to access the pedometer data using shorter epochs, but it is labor intensive because the data are in a different format and would need reformatting to be compared temporally alongside the accelerometer data. Therefore, it would be difficult to correct for frequency-dependent filtering in field-based studies.

Yamax Pedometer

The Yamax Digiwalker SW-200 (Tokyo, Japan) was used. This unit measures vertical oscillations, with the only output being a total count of the accumulated movements. The Yamax will record up to 99,999 accumulated steps. Data (Yamax) were expressed as steps per minute.

Data Analysis

Descriptive statistics were calculated for all output variables. No significant side-to-side differences were

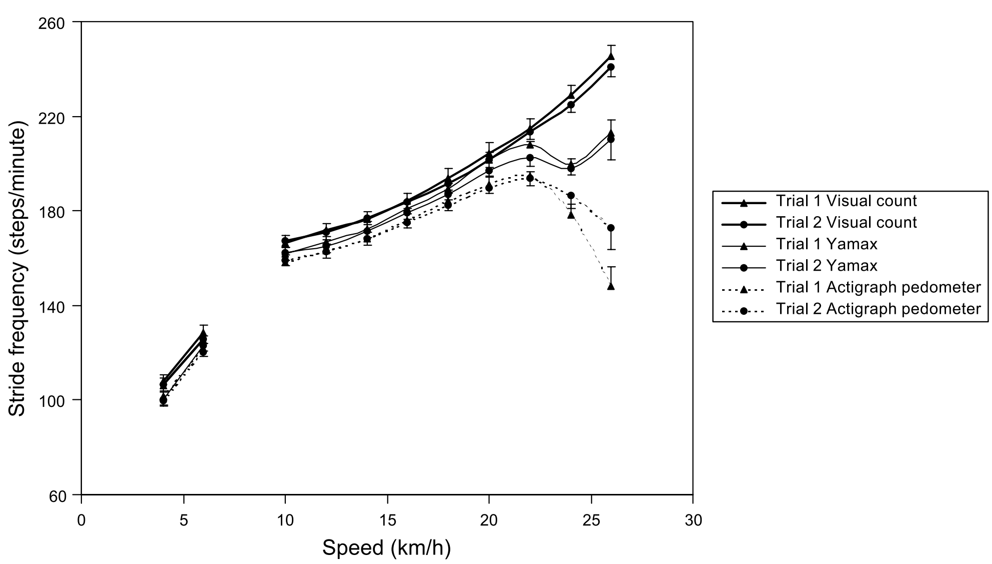

FIGURE 1—Comparison of actual step frequency (visual count) with step frequency recorded by the Yamax pedometer and the ActiGraph pedometer (ActPed) across trial and speed.

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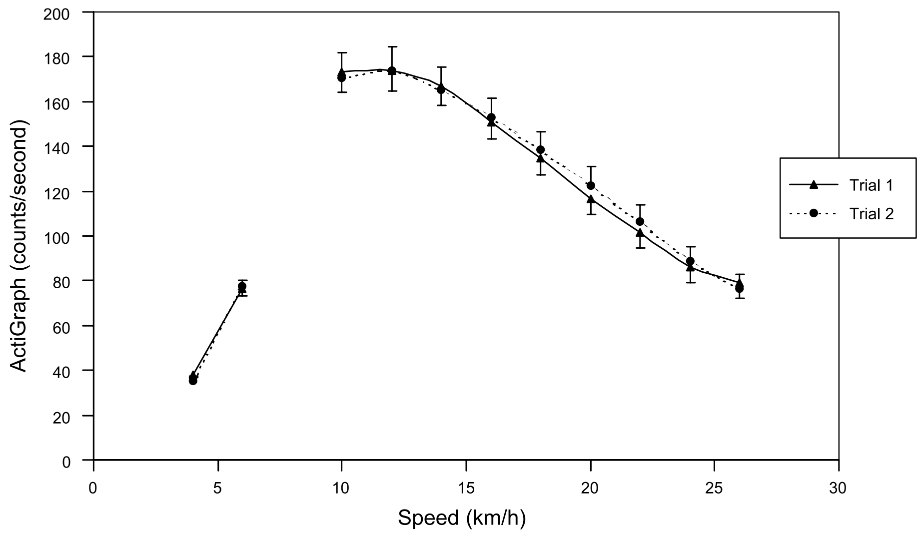

FIGURE 2—Comparison of ActiGraph counts across trial and speed.

evident for any monitor ($P > 0.05$), so the means of left and right data were used in all analyses. Running the analyses for the left and right monitors separately did not change the results, so only the results from the mean data are presented. Alpha was set at 0.05 unless otherwise indicated. All *post hoc* tests were carried out using one-factor repeated-measures ANOVA, paired *t*-tests, or Tukey tests (adapted for repeated measures (23)) as appropriate. Bonferroni adjustments were used to control for the inflated risk of type I error attributable to multiple tests. SPSS version 11.0 (SPSS Inc., Chicago, IL) was used for all statistical analyses.

Comparison by speed and trial. Differences between step frequency (visual count) and steps recorded by the Yamax and the ActPed across speed and trial were investigated using a three-factor fully repeated-measures ANOVA. The effects of speed and trial on the ActiGraph, CorrACT, and RT3vm were investigated using a series of three, two-factor, fully repeated-measures ANOVA. To investigate the relative importance of the three RT3 axes across speeds, differences between the **x**, **y**, and **z** vectors of the RT3 across speed and trial were investigated using a three-factor fully repeated-measures ANOVA.

Reliability. Test–retest reliability for step frequency, Yamax, ActPed, ActiGraph, and RT3vm was investigated using a series of intraclass correlations (ICC, two-way mixed Cronbach alpha model). All speeds were assessed separately.

Relationships between speed, step frequency, and monitor output. The correlation between speed, step frequency, and each of the output variables was determined for each individual and for each trial. The distribution of correlation coefficients (r) is skewed (20). Therefore, r was converted to z_r, using Fisher's transformation, to obtain a more normal distribution. The mean z_r for all participants was calculated and converted back to r. The proportion of participants with significant correlations for each output variable was also calculated.

Correlations also were calculated between step frequency and output variables separately for frequencies

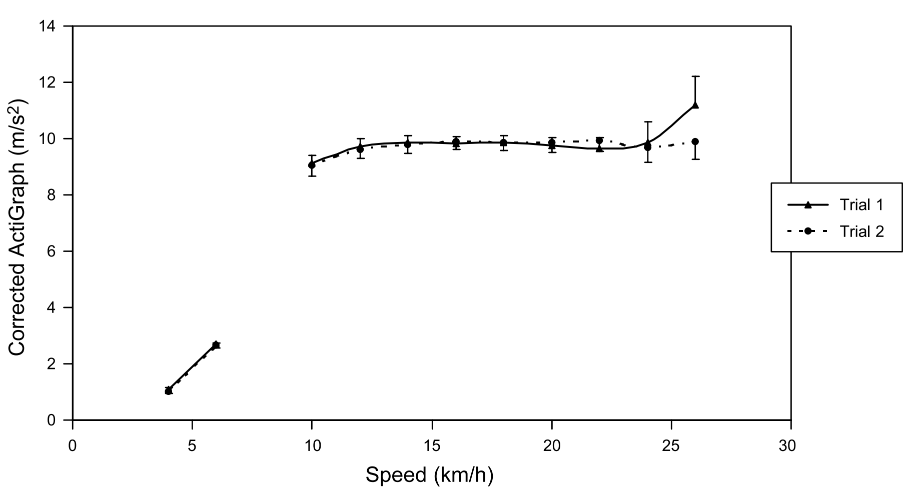

FIGURE 3—Comparison of ActiGraph counts, corrected for frequency-dependent filtering, across trial and speed.

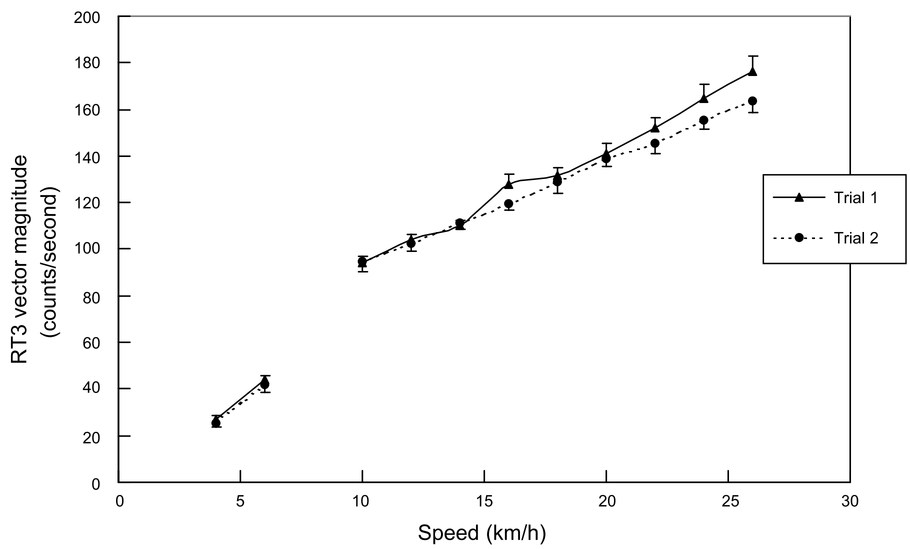

FIGURE 4—Comparison of RT3 vector magnitude (vm) counts across trial and speed.

below 2.5 Hz (walking) and frequencies above 2.5 Hz (running). However, because of insufficient data points per participant for meaningful correlations, particularly for walking, data from all participants were entered into each correlation. This violates the assumption of independence of data points for correlational analysis (9); hence, the results are only intended as a guide to the differing relationships at low and high frequencies. Correlations were calculated separately for trial 1 and trial 2. These were converted to z_r as described above; the mean was calculated and was converted back to r.

Intramonitor variability. To investigate how representative epochs of different lengths were of steady-state activity, successive data points from the 1-s epoch file were averaged to obtain data files reflecting 5-, 10-, and 15-s epochs for each monitor. This was carried out for all speeds assessed for 60 s (i.e., speeds of 4–18 km·h^{-1}). The entire 60 s were analyzed for each speed. Therefore, 1-s epoch files contained 60 data points, 5-s epoch files contained 12 data points, 10-s epoch files contained six data points, and 15-s epoch files contained four data points. The coefficient of variation (CV) of data points within each of these files was calculated for each participant. The CV of data from the four epochs were compared between monitors and across speeds using a three-factor fully repeated-measures ANOVA.

RESULTS

Comparison by speed and trial. There were no main effects for trial, or interactions involving trial, for any of the output variables.

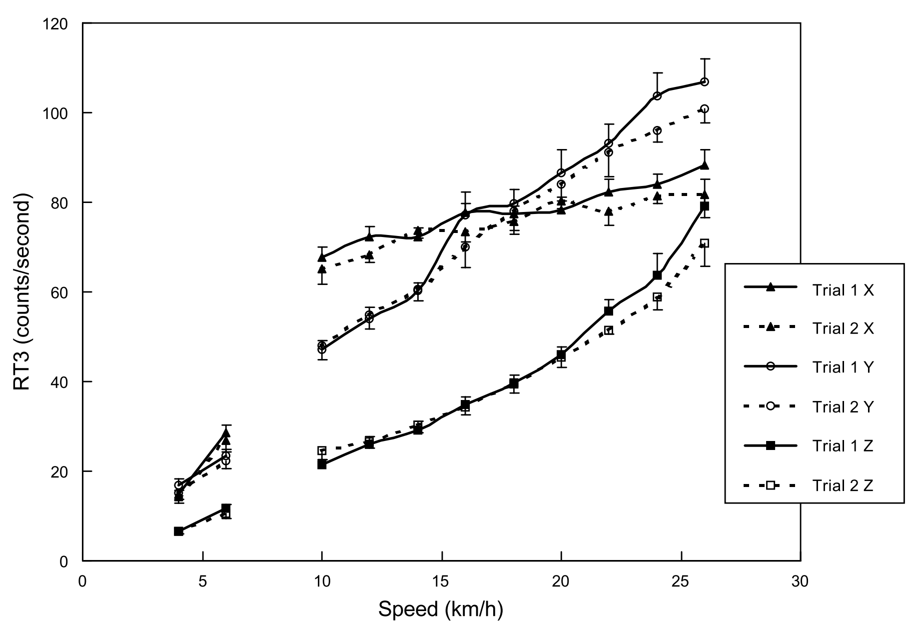

FIGURE 5—Comparison of RT3 counts on the vertical (x), anteroposterior (y), and mediolateral (z) vectors across trial and speed.

TABLE 1. Intraclass correlations by measure and speed.

Speed ($km \cdot h^{-1}$)	Step Frequency (Visual Count)	Yamax Pedometer	ActPed	ActiGraph	RT3vm
4	0.96	0.56*	0.70*	0.84	0.94
6	0.71	0.91	0.90	0.93	0.76
10	0.94	0.90	0.94	0.97	0.86
12	0.95	0.94	0.93	0.98	0.90
14	0.90	0.86	0.90	0.97	0.51*
16	0.91	0.88	0.90	0.98	0.58*
18	0.85	0.88	0.88	0.97	0.58*
20	0.90	0.52*	0.88	0.97	0.73
22	0.87	0.53*	0.40*	0.94	0.83
24	0.90	0.88	0.45*	0.91	0.60*
26	0.87	−0.19*	0.42*	0.89	0.68*

* Nonsignificant ($P > 0.05$).

Pedometers. The step-frequency analysis revealed a significant main effect for speed ($F_{10,70} = 327.6$, $P < 0.001$) and monitor ($F_{2,14} = 55.1$, $P < 0.001$) and a significant speed × monitor interaction ($F_{20,140} = 26.3$, $P < 0.001$) (Fig. 1). A series of 11 one-factor repeated-measures ANOVA were used to investigate the differences between monitors at each speed, and three one-factor repeated-measures ANOVA were used to investigate the differences across speed for each monitor. Paired *t*-tests were used to follow up main effects.

The step frequency assessed by visual count was significantly different at each speed from all other speeds. The Yamax differentiated between all speeds below 16 $km \cdot h^{-1}$, except 10 and 12 $km \cdot h^{-1}$, which were not significantly different. The step counts for the Yamax for speeds greater than 16 $km \cdot h^{-1}$ were not significantly different from each other but were greater than for speeds below 16 $km \cdot h^{-1}$. The ActPed differentiated between all speeds up to 16 $km \cdot h^{-1}$, except for 10 and 12 $km \cdot h^{-1}$. However, speeds of 10 $km \cdot h^{-1}$ and above were not different from speeds of 24 and 26 $km \cdot h^{-1}$. At all speeds, the visual step-count frequency and the Yamax measurement were significantly greater than the ActPed measurement. At all speeds except 20 $km \cdot h^{-1}$, the visual step-count frequency was greater than the Yamax.

Accelerometers. Both accelerometers and the corrected ActiGraph output showed main effects for speed (ActiGraph $F_{10,70} = 97.4$, $P < 0.001$; CorrACT $F_{10,70} = 140.2$, $P < 0.001$; RT3vm $F_{10,70} = 334.1$, $P < 0.001$; Figs. 2–4). ActiGraph output increased significantly across speeds 4, 6, and 10 $km \cdot h^{-1}$ (Fig. 2). However, it then peaked and began to progressively decline, such that there were no significant differences between speeds of 10 and 16 $km \cdot h^{-1}$, and counts declined to the extent that all speeds greater than 16 $km \cdot h^{-1}$ produced counts significantly lower than at 10–16 $km \cdot h^{-1}$. Furthermore, counts from walking at 6 $km \cdot h^{-1}$ were not significantly different from counts from running at 20–26 $km \cdot h^{-1}$. Correcting the ActiGraph output for frequency-dependent filtering (CorrACT) prevented the decline in counts (Fig. 3). The output increased significantly to a speed of 10 $km \cdot h^{-1}$. However, output then plateaued, and there were no further increases with speed.

The RT3vm increased significantly with successive speeds up to 16 $km \cdot h^{-1}$, except 10 and 12 $km \cdot h^{-1}$, which were not significantly different from each other. Counts at 18, 20, and 22 $km \cdot h^{-1}$ were not significantly different from each other but were significantly greater than at speeds below 16 $km \cdot h^{-1}$ and lower than at speeds of 24 and 26 $km \cdot h^{-1}$ (Fig. 4).

Regarding the three vectors of the RT3, as well as the main effect for speed ($F_{10,70} = 334.1$, $P < 0.001$), there was a significant main effect of vector ($F_{2,14} = 133.2$, $P < 0.001$) and speed × vector interaction ($F_{20,140} = 23.5$, $P < 0.001$) (Fig. 5). A series of three, one-factor, repeated-measures ANOVA were used to investigate the differences between speeds for each vector, and 11 one-factor repeated-measures ANOVA were used to investigate the differences between vectors at each speed. Paired *t*-tests were used to follow up main effects. The vertical vector (**x**) increased significantly up to 10 $km \cdot h^{-1}$ but then plateaued, and there was no further increase with speed. Generally, the anteroposterior vector (**y**) increased significantly with speed, but with no significant differences between some consecutive speeds: 12 and 14 $km \cdot h^{-1}$, 14 and 16 $km \cdot h^{-1}$, 16–20 $km \cdot h^{-1}$, and 22–26 $km \cdot h^{-1}$. Similarly, the mediolateral vector (**z**) generally increased significantly with speed, but with no significant differences between some consecutive speeds: 10 and 12 $km \cdot h^{-1}$, 12 and 14 $km \cdot h^{-1}$, 14 and 16 $km \cdot h^{-1}$, 18 and 20 $km \cdot h^{-1}$, and 22–26 $km \cdot h^{-1}$. At speeds up to 14 $km \cdot h^{-1}$, the vertical vector had the greatest magnitude. There were no differences between the vertical and the anteroposterior vector at speeds of 16 and 20 $km \cdot h^{-1}$, and at speeds exceeding 20 $km \cdot h^{-1}$, the anteroposterior vector had the greatest magnitude.

TABLE 2. Summary of individual correlations of activity monitor output with speed and step frequency.

Activity Measure	Speed		Step Frequency	
	Mean *r*	Proportion Significant ($P < 0.01/P < 0.05$)	Mean *r*	Proportion Significant ($P < 0.01/P < 0.05$)
Yamax pedometer	0.943	100/100	0.968	100/100
ActPed	0.828	70/75	0.878	74/85
ActiGraph	0.023	0/0	0.156	0/0
Corrected ActiGraph*	0.771	53/100	0.847	100/100
RT3 vector magnitude	0.968	100/100	0.980	100/100
RT3x (vertical)	0.857	95/100	0.903	95/100
RT3y (anteroposterior)	0.975	100/100	0.968	100/100
RT3z (mediolateral)	0.968	100/100	0.953	100/100

* Corrected for frequency-dependent filtering (Brage et al. (7)).

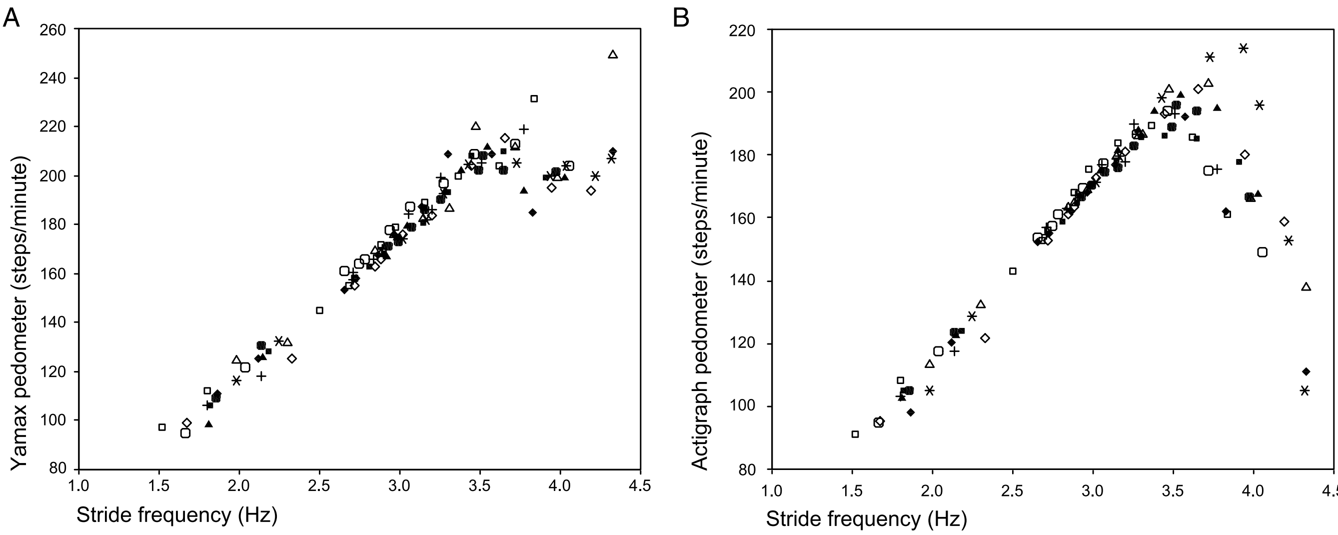

FIGURE 6—The relationship of pedometer steps with step frequency for all participants (each participant is represented by a different symbol). ***A*, Yamax pedometer; *B*, ActiGraph pedometer (ActPed).**

Reliability. Average measures of ICC by monitor and speed are presented in Table 1. These were generally high (> 0.80) and significant for all speeds greater than 4 km·h^{-1} and lower than 20 km·h^{-1}. However, for step frequency and the ActiGraph, ICC were high and significant throughout. The lowest reliability was exhibited by the RT3vm, with nonsignificant ICC (0.51–0.68) at several midrange and high speeds.

Relationships between speed, step frequency, and monitor output. Correlations assessing the relationship of activity monitor output with speed or step frequency were strong (> 0.75), except for the ActiGraph (Table 2). Correlations with step frequency were generally higher than those with speed. Figures 6–8 show the similarity of the relationships between output measures and step frequency between participants. The ActiGraph output showed no relationship with speed or step frequency, because of its decline with increasing running speeds (Fig. 7A). However, correcting the ActiGraph for frequency-dependent filtering greatly improved the relationships, giving a mean correlation of 0.771 with speed and 0.847 with step frequency (Fig. 7B). The strongest relationships with speed and step frequency were found for the anteroposterior (**y**) (r = 0.968–0.975, Fig. 8C), mediolateral (**z**) (r = 0.953–0.968, Fig. 8D), and vector magnitude of the RT3 (r = 0.968–0.980, Fig. 8A) and also for the Yamax (r = 0.943–0.968, Fig. 6A).

Splitting the analyses into walking and running speeds improved the correlations between the ActiGraph and step frequency for walking (Table 3). However, the correlations

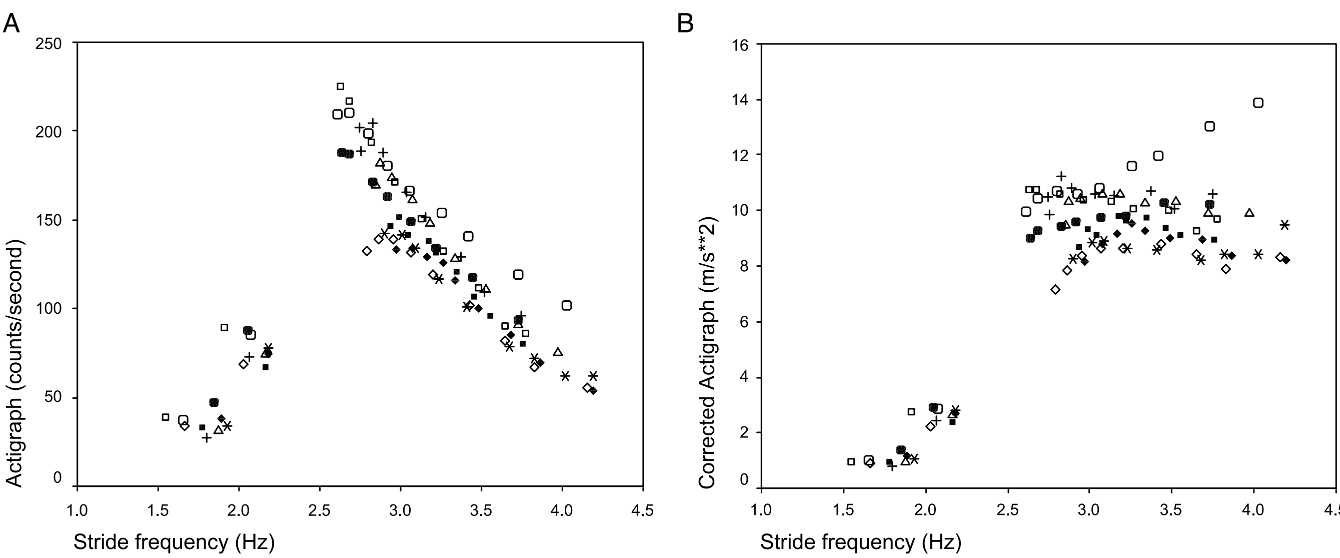

FIGURE 7—The relationship of ActiGraph counts with step frequency for all participants (each participant is represented by a different symbol). ***A*, ActiGraph (counts per second); *B*, ActiGraph output corrected for frequency-dependent filtering (m·s^{-2}).**

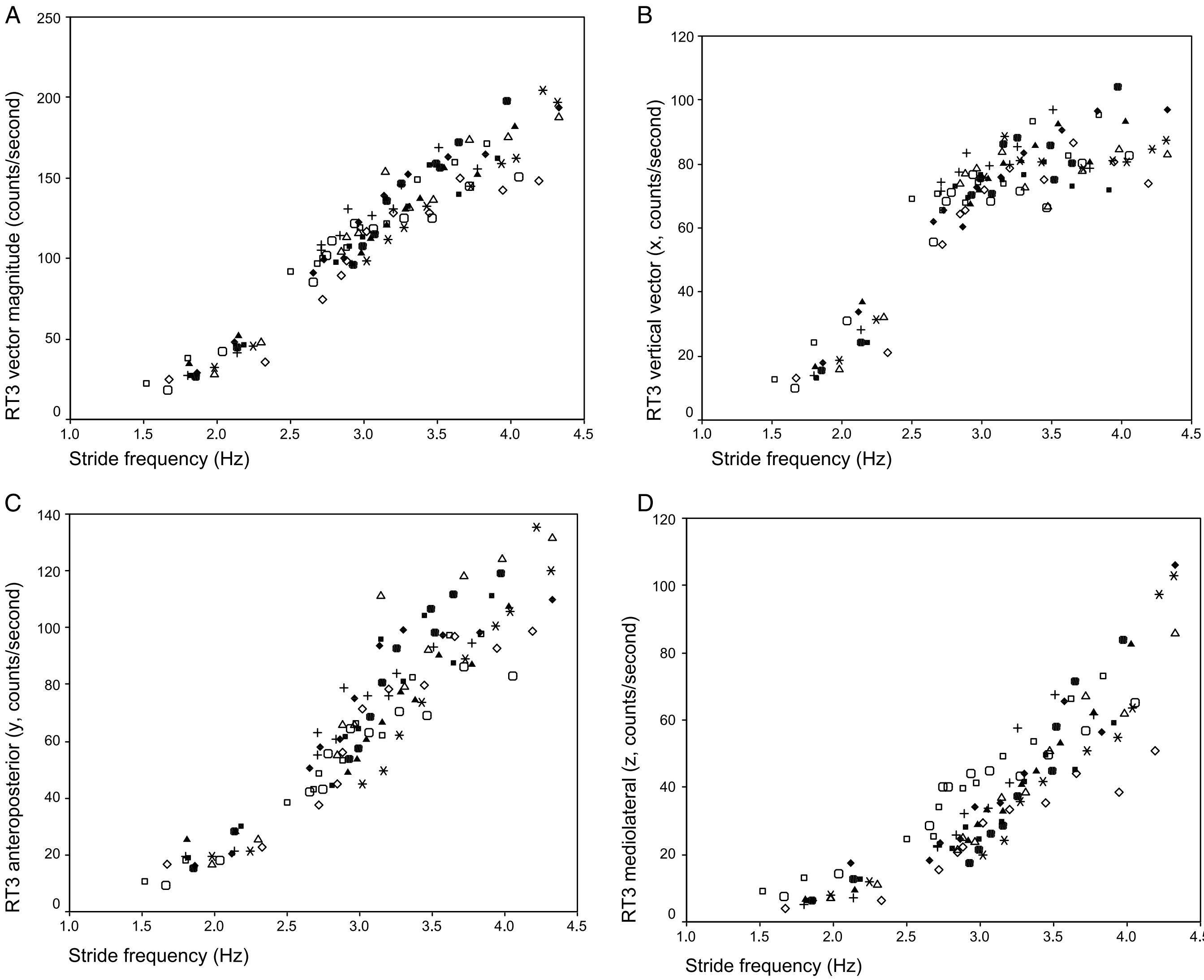

FIGURE 8—The relationship of RT3 with step frequency for all participants (each participant is represented by a different symbol). *A*, RT3 vector magnitude (vm, counts per second); *B*, RT3 vertical vector (x, counts per second); *C*, RT3 anteroposterior vector (y, counts per second); *D*, RT3 mediolateral vector (z, counts per second).

(ActiGraph = 0.656, CORRact = 0.771, both $P < 0.01$, Fig. 7A and B) were still lower than for the pedometers ($r > 0.95$, $P < 0.01$, Fig. 6A and B) and the RT3 vertical (**x**) and vector magnitude ($r > 0.80$, $P < 0.01$, Fig. 8A and B). At frequencies greater than 2.5 Hz, the Yamax, RT3 vector magnitude, anteroposterior (**y**), and mediolateral (**z**) all correlated strongly with step frequency ($r > 0.80$, $P < 0.01$, Figs. 6A, 8A, C, and D). The strongest correlation was the ActiGraph (−0.921, Fig. 7A), but this was negative, reflecting the sharp decline in counts with increasing running speeds.

Intramonitor variability. There was a significant monitor × speed × epoch interaction for the CV of activity output ($F_{1.8,\ 16.2} = 5.0$, $P < 0.001$). Regardless of the speed or epoch setting, it was clear that the ActiGraph values were far lower than the RT3 values (Fig. 9A and B), so this interaction was followed up with two, two-factor speed × epoch ANOVA: one for the ActiGraph and one for the RT3. Two-way speed × epoch interactions were evident for the ActiGraph ($F_{18,162} = 2.9$, $P < 0.001$) and the RT3 ($F_{18,162} = 5.5$, $P < 0.001$).

For the ActiGraph, *post hoc* Tukey tests showed that there were no differences between the CV for different

TABLE 3. Correlations between step frequency and activity monitor output stratified by low-frequency (< 2.5 Hz) and high-frequency (> 2.5 Hz) activities.

	Correlation with Step Frequency (Hz)	
Activity Measure	**< 2.5 Hz**	**< 2.5 Hz**
Yamax pedometer	0.954	0.827
ActPed	0.958	0.279†
ActiGraph	0.656	−0.921
Corrected ActiGraph*	0.771	0.145‡
RT3 vector magnitude	0.814	0.861
RT3x (vertical)	0.803	0.533
RT3y (anteroposterior)	0.755	0.830
RT3z (mediolateral)	0.593	0.847

* Corrected for frequency-dependent filtering (Brage et al. (7)).
All significant ($P < 0.01$), except † ($P < 0.05$) and ‡ (not significant, $P > 0.05$).

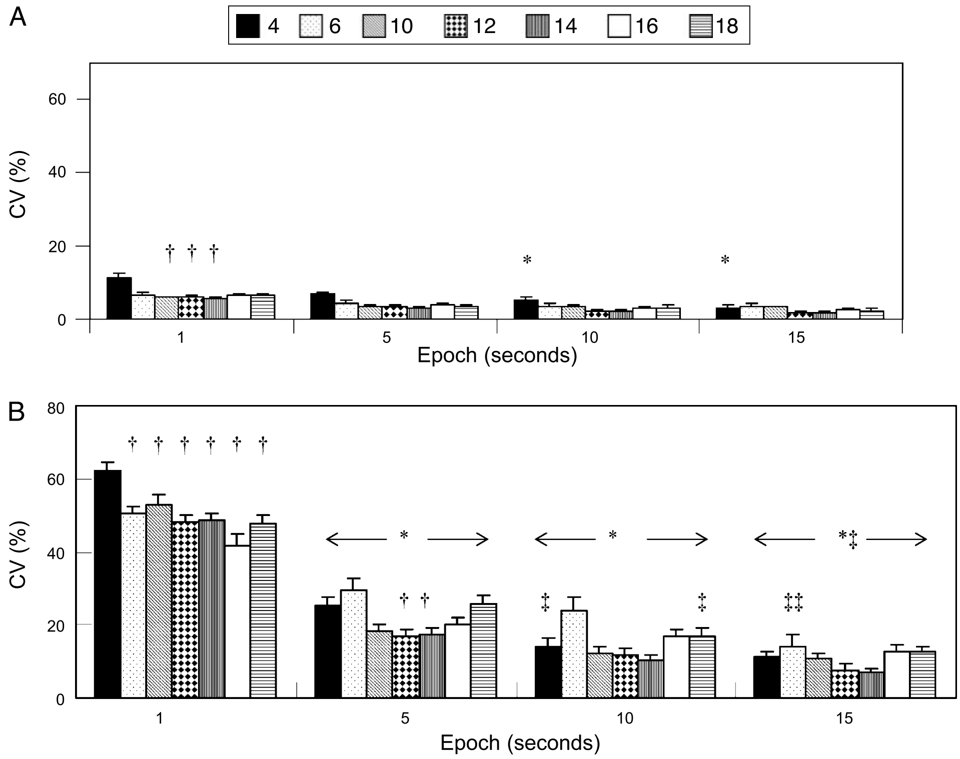

FIGURE 9—The effect of epoch duration (1, 5, 10, and 15 s) on CV (%) of accelerometer output at each speed. *A*, ActiGraph (counts per second); *B*, RT3 vector magnitude (counts per second). CV is higher for the RT3 than the ActiGraph in all cases. * Significantly lower than 1-s epoch, within speed ($P < 0.05$); ‡ significantly lower than 5-s epoch, within speed ($P < 0.05$); ‡‡ significantly lower than 10-s epoch, within speed ($P < 0.05$); † significantly different from 4 km·h^{-1}, within epoch ($P < 0.05$).

epochs, except at 4 km·h^{-1}, where the 1-s epoch had a higher CV than the 10- and 15-s epochs ($P < 0.05$, Fig. 9A). For the RT3, *post hoc* Tukey tests showed that the CV of the 1-s epoch was consistently higher than the 5-, 10-, and 15-s epochs ($P < 0.05$), regardless of speed (Fig. 9B). Similarly, the CV of the 5-s epoch was higher than that of the 15-s epoch regardless of speed.

DISCUSSION

This study compared the validity of several commercially available activity monitors across a range of walking and running speeds. All output measures from each of the monitors demonstrated a good relationship with walking speed. However, the ActiGraph uniaxial accelerometer peaked at 10 km·h^{-1} and progressively declined with increasing running speed. Conversely, the RT3 triaxial accelerometer was linearly related with speed throughout. The simple Yamax pedometer and the output from the ActiGraph pedometer function were linearly related with speed up to 20 km·h^{-1}, although both pedometers, particularly the ActPed, underestimated the number of steps.

The use of short activity bouts (30–60 s) precluded the use of steady-state energy-expenditure measures as a criterion, although it allowed the testing of the monitors at high running speeds. In daily life, physical activity frequently consists of short bouts, particularly when activity is intense (2,27). Accelerometers are capable of assessing activity at epochs as low as 1 s; therefore, they have potential for the assessment of these bouts. Because we were unable to obtain steady-state measures of oxygen consumption, from which to estimate energy expenditure, we used speed as an indicator of energy expenditure. Speed (3–20 km·h^{-1}) and mass-specific oxygen consumption are highly related in young male adults ($R^2 = 0.97$, 5).

Validity. As expected, increases in step frequency with speed were relatively greater at walking speeds than at running speeds. A curvilinear relationship between step frequency and running speed was evident, with proportionately greater increases in step frequency at speeds greater than 20 km·h^{-1}, as described by Dillman (8). Below this speed, the pedometers showed a strong linear relationship with step frequency, although both devices significantly underestimated actual step counts. The magnitude of this underestimation was approximately five steps per minute for the Yamax and 10 steps per minute for the ActPed for speeds below 20 km·h^{-1}. The underestimation of step frequency by the pedometers increased when step frequency was greater than 3.5 Hz. This was particularly evident for the ActPed, where pedometer counts declined when step frequency exceeded 3.5 Hz. These results indicate that the greater the proportion of high-intensity activity in a given day, the greater the potential underestimation of habitual daily activity when assessed by pedometry. It is possible that the design of this study was responsible for the underestimation below 20 km·h^{-1} for the Yamax pedometer; data points could not be removed from the beginning and end of the 60-s period (as with software-based accelerometers and the ActPed) to ensure that all output represented steady running. Previous research has shown the Yamax (3,13) and the ActPed (13) accurately assess step counts at walking speeds.

The decline of ActiGraph counts at speeds greater than 10 km·h^{-1} corresponded with a step frequency of 2.5–3.0 Hz. At frequencies above 2.28 Hz, the filter weight in the ActiGraph is < 0.50 (25)—hence the decline in output at these step frequencies. At frequencies of 4 Hz, the filter weight is 0.2 (6). This explains why output at speeds with step frequencies between 3.5 and 4.5 Hz were approximately one fifth to two fifths of the peak values obtained and did not differ from the output when walking at 6 km·h^{-1}. The occurrence of peak ActiGraph counts at 10 km·h^{-1}, and a tendency to decline with higher speeds (up to 20 km·h^{-1}), has been reported previously (5). However, the decline in the current study is far greater than has been shown previously; the counts at 20 km·h^{-1} are 70% of those obtained at 10 km·h^{-1}, compared with 90% in the study by Brage et al. (5). This may reflect the slightly higher step frequencies observed in the current study leading to a greater degree of filtering and, hence, lower ActiGraph output.

Removal of the effect of frequency-dependent filtering, by converting ActiGraph counts to acceleration, eliminated the decline in counts, but the output still plateaued at speeds greater than 10 km·h^{-1}. This reflects the limited change in vertical displacement of the body with increases in running speed (8) and also explains the leveling off of RT3 vertical counts. In contrast, the anteroposterior, mediolateral, and vector magnitude of the RT3 were linearly related with speed and step frequency throughout the range of speeds tested, reflecting the importance of horizontal acceleration at higher speeds (8). Because the vector magnitude incorporates all three vectors, it accounts for the variance in the relative dominance of the vectors across the different speeds. This demonstrates the importance of the triaxial RT3 when a wide range of activity intensities is of interest.

The decline in ActiGraph counts at high intensity is particularly troublesome because output for walking at 6 km·h^{-1} was not different from running at 20–26 km·h^{-1}. As a result, vigorous or hard activity would be misclassified. The conversion to acceleration (CORRact) would prevent this and would ensure that all speeds equivalent to a slow run or faster would be classified as vigorous. However, as the output reached a ceiling at 10 km·h^{-1}, it would not be possible to classify activity into intensities greater than vigorous. As already discussed, correcting for frequency-dependent filtering in a field study would be very labor intensive and would necessitate the programming of the ActiGraph to simultaneously collect step and acceleration data.

Reliability. Monitors did not differ significantly across trials, and ICC were high for the pedometers and the ActiGraph. Reliability tended to be lowest at 4 km·h^{-1} and at speeds greater than 20 km·h^{-1}. A previous study identified relatively lower reliability for the RT3 when tested at low frequencies in a mechanical setup (19). Reliability in the current study reflects both intrainstrument variability and human variability between the two trials. It is possible that there was more within-participant variability at high and low speeds. Certainly, the difference between step frequency in trial 1 and trial 2 was greatest at speeds above 20 km·h^{-1}, though this was not significant. The RT3 showed the poorest reliability overall in that the ICC was low for midrange speeds and for speeds at the extremes of the range. Low ICC at given speeds may reflect the smaller range in the RT3 data within speed, compared with the ActiGraph data. When all speeds were analyzed together, ICC were high and significant for both the RT3 ($r = 0.98$, $P < 0.001$) and the ActiGraph ($r = 0.99$, $P < 0.001$). Reported coefficients of variation for interunit and intraunit variability assessed on mechanical apparatus are higher for the RT3 (19) than the ActiGraph (15).

Intramonitor variability. To capture high-intensity sporadic activity, the use of short epochs is recommended. It has been shown with both the ActiGraph (18) and the RT3 (21) that the use of longer epochs leads to an underestimation of children's vigorous- and high-intensity activity (i.e., greater than 6 METs). This is because of the smoothing of output, representing short bursts of high-intensity activity during a 60-s period, resulting in the illusion of a longer period of moderate activity. Choice of epoch does not influence the estimate of total activity, only time spent at different intensities.

Results from this study show a high degree of variability in data collected from the RT3 during constant-intensity activity at 1-s epochs. The ActiGraph samples data at 30 Hz (1), explaining the relatively low CV associated with this unit, even when using 1-s epochs. The sampling frequency of the RT3 is not available from the manufacturers. When data were collapsed into 5-s epochs, the variability across data points was much improved but was still significantly higher when compared with 15-s epochs, and was substantially higher than the variability for the ActiGraph regardless of epoch. However, the variability of the data from 10-s epochs did not differ from that of the 15-s epochs. Therefore, we suggest that if the temporal nature of short bursts of activity is of interest, the smallest usable epoch that can be used to obtain a reliable measure of activity is 5 s or, preferably, 10 or 15 s, with the RT3. It is, however, possible to look at second-by-second activity with the ActiGraph. However, the choices for epoch with the RT3 are 1 or 60 s. The option of a 5- or 10-s epoch would not only provide a more reliable output measure; it would mean data could be collected for 5 or 10 times as long. Considering that the RT3 can only collect data for 9 h when set at a 1-s

APPLIED SCIENCES

epoch, the option of 5- or 10-s epochs would increase its utility considerably.

We acknowledge that the use of a large number of statistical comparisons in this study has increased the risk of type 1 error. The Bonferroni correction was used in *post hoc* comparisons to control for this increased error rate, but not in the initial analyses. However, results were generally highly significant ($P < 0.001$) and remain significant if the Bonferroni correction is applied to the alpha level for the initial analyses. Furthermore, results were as hypothesized in accordance with the literature and theory.

Summary. The increasing underestimation of activity by the ActiGraph as speed increases is related to frequency-dependent filtering and the assessment of acceleration in the vertical plane only. The RT3 vector magnitude was linearly related to speed, reflecting the measurement of horizontal acceleration, which is dominant at higher speeds. These results indicate that high-intensity activity would be underestimated by the ActiGraph, even after conversion to acceleration to correct for frequency-dependent filtering, but not by the RT3. However, it should be noted that the reliability of the RT3 units used in this study was inferior to that of the ActiGraph units. Pedometers offer a fairly accurate step count, even at relatively high step frequency, and they show high reliability.

The ActiGraph provides similar data for activity performed at a constant rate, regardless of whether the monitor is set at a 1- or 15-s epoch. However, to obtain a representative measure of constant-rate activity from the RT3, an epoch of 5 s, or even 10–15 s, is needed. This indicates that bouts of activity shorter than 5–10 s cannot be accurately described by the RT3.

The results from this study are limited to male runners, and it is questionable how generalizable our results are to children, women, and nonrunners. However, the study by Brage et al. (6) shows that declines in ActiGraph counts with speed also occurred in children at speeds greater than 9 $km \cdot h^{-1}$; the earlier decline in counts reflects the greater step frequency for children at any given speed. This also may be the case in women because, on average, women are shorter and, therefore, have higher stride frequency at any given speed. Additionally, there are other commercially available uniaxial accelerometers that we did not test. However, the results regarding uniaxial accelerometry and the vertical vector of the RT3 reflect the lack of change in vertical acceleration of the body at high speeds; therefore, they probably are representative of other uniaxial accelerometers. It would be interesting to investigate the performance of omnidirectional accelerometers at high speeds.

Accurate assessment of high-intensity activity is important in a number of scenarios—for example, when assessing relationships between activity and bone health. When selecting activity monitors, researchers should consider the intensity of activity they need to be able to assess and the epoch length needed to address the primary research question(s). If the capture of high-intensity activity is important, triaxial accelerometers may be more appropriate than uniaxial accelerometers. Careful consideration of the findings from this study and from other similar studies will allow the researcher to make an informed choice regarding the most appropriate activity monitor.

APPLIED SCIENCES

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