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The number of strides required for treadmill running gait analysis is unaffected by either speed or run duration

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Abstract

Participation in running events has increased recently, with a concomitant increase in the rate of running related injuries (RRI). Mechanical overload is thought to be a primary cause of RRI, it is often detected using motion analysis to examine running mechanics during either overground or treadmill running. In treadmill running, no clear consensus for the number of strides required to establish stable kinematic data exists. The aim of this study was to establish the number of strides needed for stable data when analysing gait kinematics in the stance phase of treadmill running. Twenty healthy, masters age group, club runners completed a high intensity interval training run (HIIT) and an energy-expenditure matched medium intensity continuous run (MICR). Thirty consecutive strides at start and end of each run were identified. Sequential averaging was employed to determine the number of strides required to establish a stable value. No significant differences existed in the number of strides required to achieve stable values. Twenty consecutive strides are required to be 95% confident stable values exist for maximum angle, angle at initial foot contact, and range of motion at the ankle, knee, and hip joints variables at the ankle, knee, and hip joints, in all three planes of motion, and spatiotemporal regardless of running speed and time of capture.

Keywords:

Biomechanics, motion analysis, kinematics, gait

1. Introduction

Running popularity has increased in recent years with the launch of events such as The Parkrun, a weekly 5-km run that began in 2004. It began in a single location in the UK and now has approximately 105,000 participants per week (Parkrun, 2018). Parkrun participants, who are mainly club or recreational runners, exhibit high rates of running related injuries (RRI), with 49.8 % of runners reporting an injury (Linton & Valentin, 2018). Mechanical overload is thought to be a key risk factor for development of RRI (Hreljac, 2004). Through the analysis of kinematic and spatiotemporal running patterns, differences have been identified between injured and non-injured runners and changes within a run due to fatigue (Dierks, Davis, & Hamill, 2010; Miller, Lowry, Meardon, & Gillette, 2007; Willson, Loss, Willy, & Meardon, 2015). Commonly this is analysed using motion capture analysis to assess running mechanics during over ground and treadmill running. There are, however, methodological considerations that need to be made when designing studies investigating running related injuries or fatigue using motion analysis. With the underlying aetiology of running related injuries still uncertain, one approach has been to examine fatigue related changes in gait by comparing the beginning and end of a run (Dierks et al., 2010). To date no study has addressed whether stable data are achieved in the same number of strides as runners fatigue.

The most widely used approach for data capture has been overground running, usually requiring participants to run over a force platform while simultaneously being filmed. Using this approach, it is only possible to measure a single stride (D. M. Bazett-Jones et al., 2013; David M. Bazett-Jones et al., 2013; Brown, Zifchock, & Hillstrom, 2014; Brown, Zifchock, Hillstrom, Song, & Tucker, 2016), however the number ground contacts collected in an experiment may influence stability of the data collected (Bates, Osternig, Sawhill, & James, 1983). Multiple trials are therefore required to gather enough data for analysis. In these circumstances it is difficult to standardise the running speed with studies often allowing a speed variation of between ±5% to 10% of the designated running speed (Almonroeder & Benson, 2016; D. M. Bazett-Jones et al., 2013; Riley et al., 2008; Sinclair et al., 2013). Moreover, the time taken to record multiple contacts will enable recovery to occur, possibly precluding the examination of fatigue effects (Froyd, Millet, & Noakes, 2013). Treadmill running by contrast enables continuous data collection at a constant speed. Running gait contains a natural variability, whose capture might provide insight into gait control, for example a reduction in variability has been linked with injury (Hamill, Palmer, & Van Emmerik, 2012). Treadmill running therefore offers a more consistent environment to capture this variability.

While treadmill running offers a more consistent environment for data capture, less clear is the number of strides required to have a sufficiently stable gait to analyse kinematic parameters. A few studies have reported the number of consecutive strides required for assessing running kinematics with values ranging from 5-50 (Dierks et al., 2010; Esculier, Roy, & Bouyer, 2015; Ford, Taylor-Haas, Genthe, & Hugentobler, 2013; Miller et al., 2007; Riley et al., 2008). No set criteria or guidelines exist for the number of successive strides required to establish stable kinematic or spatiotemporal values during treadmill running. These, kinematic and spatiotemporal parameters vary with running speed (Orendurff et al., 2018), again this has not been sufficiently well examined to provide guidelines. The aims of this study were i) to determine the number of strides necessary to produce stable values for kinematic and spatiotemporal assessment during treadmill running; ii) to compared two different running speeds: a high intensity interval run (HIIT) and a medium intensity continuous run (MICR); iii) to compare values at the start and end of a run.

2. Methods

2.1 Research Design

Runners were filmed at the beginning and end of two runs in a pre-post, repeated measures crossover design. The two runs were matched for energy expenditure but differed in intensity. The recordings were used to identify the number of strides required to achieve stable kinematic and spatiotemporal values across different intensities and levels of fatigue.

2.2 Participants

Based on a power analysis and subsequent institutional ethical approval, for calculating kinematic variables (desired effect size = 0.66) 20 healthy, experienced, local club distance runners, (N=10 male; N=10 female) were recruited. A description of participant characteristics, treadmill speeds and run duration is provided in Table 1. Participants were excluded if they had not competed in an organised race within the past two years, were not part of an affiliated running club, or had experienced any type of lower extremity injury that prevented them from running for more than a week in the past six months. Participants were also excluded if they had experienced any cardiovascular or neurological conditions, or if they were allergic to adhesive material. Medical history was pre-screened via a self-reported questionnaire and eligible participants provided informed written consent prior to testing sessions.

2.3 Procedure

Each participant completed two treadmill runs that mimicked different, typical, training intensities. One was a HIIT session, the other a continuous run, participants were given verbal encouragement throughout. All sessions were conducted at the same time of day to minimize diurnal variation (Reilly & Garrett, 1998). Participants were asked to wear the same footwear throughout and follow their habitual dietary regimen, while refraining from high volume or intensity training within 48 hours of testing.

2.3.1 Preliminary Testing:

Initial measurements of mass, stature and all kinanthropometric measures were taken according to ISAK guidelines by an ISAK qualified practitioner. Participants completed an incremental treadmill (ELG2, Woodway, Germany) test to determine maximum steady state and $\dot{v}o_2$ max. Expired gas analysis was measured by Cortex Metalyser 3B (Leipzig, Germany), calibrated according to manufacturer's instructions prior to each test. A 5-minute warm-up run was completed to familiarise participants with the treadmill and equipment used for expired gas collections.

The sub-maximal test consisted of a series of incremental 4-minute stages at 0% gradient, separated by 60-s recovery (Smith & Jones, 2001). Stages increased by one km.h^{-1} until lactate turnpoint (LTP) had been exceeded, with the initial speed set according to the participant's current performance level. Between stages, a fingertip capillary blood sample was taken for analysis of blood lactate concentration (Biosen C-line, EKF diagnostics, Germany). Following a 15-min recovery, participants completed a $\dot{v}o_2$ max test with initial speed set at 4 km.h^{-1} below the speed at LTP (sLTP) at a 0% gradient. The treadmill speed was increased by 0.5 km.h^{-1} every 30 seconds until volitional exhaustion occurred.

2.3.2 Running intensity

The duration and speed of each run was individualised based on $\dot{V}O_2$ max and LTP. The HIIT session was a modification of the protocol used by James and Doust (2000) that caused fatigue. It consisted of six repetitions of 800 meters, run at one km.h^{-1} below the speed at $\dot{V}O_2$ max (s $\dot{V}O_2$ max), with a 1:1 work: rest ratio. The recovery was active with participants walking at 4km.h $^{-1}$. The MICR was run at halfway between the speed of lactate threshold (sLT) and sLTP, with the duration set to match the energy expenditure (EE) of the HIIT session.

2.4 Video Analysis

Running kinematics were captured via a 14-camera 3-Dimensional motion analysis system (Vicon Nexus; Vicon Motion Systems Ltd. Oxford, England) sampling at 500 Hz and calibrated before each session. The data were recorded using a Plugin Gate model (PiG), retroreflective markers were placed bilaterally on the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), thigh, lateral epicondyles of the femur, lateral shank, lateral malleoli, base of the 2nd metatarsal, and calcaneus. The markers were carefully placed, by the same researcher throughout, on the desired landmarks with double sided tape and the surrounding base was also taped down with double sided tape. Wand markers were used for the thigh and shank in order to obtain rotational movements of the joints. The participants were given compression leggings to wear to help keep the markers in place. The hip markers were taped around the hip using soft adhesive tape to avoid impeding hip movement and to ensure they remained in place throughout the run. Static capture was performed three seconds prior to treadmill running sessions. This was processed using the static plugin gait model and static subject calibration. For HIIT and MICR, kinematics were recorded for 25 seconds at the end of the first and start of the final minute of each run.

2.5 Data analysis

All markers were labelled and marker trajectories were filtered using a fourth order Butterworth filter via dynamic plug-in gait model with 6 Hz cut-off frequency. Gait identification was achieved through visual inspection of foot strike and toe off over 30 consecutive strides using the heel markers in the Z plane for each captured video.

Maximum angle (max), angle at initial foot contact and range of motion (ROM) of the ankle, knee and hip in the sagittal, frontal and transverse planes during the stance phase were extracted. For spatiotemporal variables, stride frequency (SF) and contact time (CT) were exported for analysis. All motion analysis data were processed using custom written script in Matlab (2016a, The Mathworks, Inc. Natick, MA, USA).

2.6 Statistical analysis

Mean, standard deviation (SD) and 0.25 SD values were calculated from 30 consecutive strides for each kinematic and spatiotemporal variable. Sequential averaging was used on each individual (Bates et al., 1983; Hamill & McNiven, 1990) to calculate the cumulative mean (strides 1 and 2; strides 1, 2 and 3, and so on for all consecutive stride permutations) and mean deviation (difference between 30 stride mean and each cumulative mean). A stable mean was considered as the lowest stride count plus one stride from when the mean deviation fell below 0.25 SD criterion value (C. R. James, Herman, Dufek, & Bates, 2007). Using the individual stable mean scores, a group mean value was calculated along with an upper 95% confidence interval.

A repeated two-way ANOVA was used to test for differences in strides counts across exercise intensity and time for each variable. Sequential averaging was conducted using a custom written MATLAB script (R2018a, The MathWorks, Inc., Natick, Ma, USA); ANOVA was conducted using SPSS v22.0 (SPSS Inc., Chicago, IL, USA).

3. Results

There were no significant differences (P>.05) in the number of strides required to reach a stable value between joints, planes of movement, intensity of run or beginning and end of run. For the frontal plane kinematics, the mean stride count required for stability ranged from 12-17 strides; 12-19 strides were

required in the sagittal plane kinematics; and 12-16 strides in the transverse plane (Table 2). The stability of required stride count was judged by upper 95% Confidence interval (CI). The 95% CI for the frontal plane required the highest stride count to achieve stability ranging from 17-21 strides, compared to 14-21 strides for the sagittal plane and 14-20 strides for the transverse plane.
Within spatiotemporal parameters, the stride frequency required the lowest mean value of 12-14 strides and a 95% CI of 16-18 strides across the different speeds and time points. Ground contact time required a mean of 16-17 strides and a 95% CI of 20-21 strides across the same conditions. None of these differences were significant (P>.05).

4. Discussion

This is the first study to investigate the number of strides required to establish a stable mean value for stance phase kinematic and spatiotemporal analysis in all three planes in treadmill running. There were no differences for stable mean stride count between ankle, knee or hip joints in all three planes of motion. Nor were there any differences in any variable with HIIT or MICR regardless of whether measures were taken at the start or end of either run. This consistency of the required stride count irrespective of movement plane, running intensity or time point, provides confidence that a fixed number of ground contacts can be used in all circumstances.

When investigating the effect of fatigue on running gait, previous studies have compared kinematics and spatiotemporal parameters at start and end of a run; treadmill running is advantageous in this respect enabling the capture of continuous data to better observe the time-course of changes. These results provide confidence that as the stride count required remained unchanged throughout each run the quantity of data needed is the same at the start compared to end. In addition, we chose two relative intensities, rather than the more common approach of using absolute intensities. The use of relative intensities tailored for each participant based on their physiological profile could have contributed to the stability in our scores. Using absolute intensities could cause greater variability in rates of fatigue and thus requires further study.

Similar to time course changes, there was little difference for stable stride count between the three planes of motion or joints examined. The highest stride count of 19 was observed only in one variable, during $\text{HIIT}_{\text{start}}$ for maximum hip angle in the frontal plane. For mean values, the transverse plane provided the lowest number of strides compared to the sagittal and frontal planes. The smallest mean stride count of 12 was observed during MICR_{end} for maximum ankle angle in the sagittal plane, along with other transverse plane variables. For simplicity and validity, we recommend that a stride count of 20 is required, based on the upper 95% CI, as this would cover all variables examined.

Our findings could serve as a guideline for data analysis of treadmill running kinematics. The absence of clear guidelines regarding the number of strides required is borne out by the inconsistencies across previous studies. Noehren, Pohl, Sanchez, Cunningham, and Lattermann (2012) along with Kellis and Liassou (2009) extracted five consecutive footfalls for data analysis, however both studies fall short of the 20 strides by Dierks et al. (2010) or 50 used by Esculier et al. (2015). Riley et al. (2008), established their own stable mean, however their method did not outline which joint or plane it represented. They found that 10-12 strides provided a stable mean but employed a more conservative 15 strides for kinematic assessment. Studies that have employed a low number of consecutive strides could have potentially ignored characteristics such as the natural variability. Jordan, Challis, and Newell (2006), observed that during treadmill running, fluctuations in running form exist but stride-to-stride variations tend to be low, as small as 3% CV. Although small, such variations still require enough data to be captured to record them.

In overground running repeated trials are often performed within a 5 to 10% range of a designated speed (Almonroeder & Benson, 2016; D. M. Bazett-Jones et al., 2013; Riley et al., 2008; Schache et al., 2001; Sinclair et al., 2013). Furthermore, generally, only one foot strike per run is captured during each run, often from a relatively short run-up. In order for the foot strike to be considered acceptable, the runner must make contact with an embedded force plate, often requiring more attempts than valid trials. Treadmill running by contrast, while not an exact replica of outdoor running (Riley et al., 2008), does offer greater opportunities for kinematic assessment due to a more consistent speed and the ability to record consecutive foot strikes. Additionally, because consecutive contacts can be recorded it is possible to examine the effects of fatigue on running kinematics. Overground running does not permit this due to the time taken to record a sufficient number of valid trials, during which time recovery is taking place.

The approach taken by this study for determining stride count during treadmill running was based on the sequential averaging method to establish a stable mean (Bates et al., 1983). How many reference trials to use appears to be an arbitrary decision. Bates et al. (1983) compared 10 and 20 reference trials, finding both identified eight non-consecutive trials were necessary for a stable mean in ground reaction force during running. To date there are no data for running kinematic or spatiotemporal values using sequential averaging. Similarly, the 0.25 SD criterion used is also an arbitrary value. James et al. (2007) compared sequential averaging with the use of ICCs and found lower stable values with ICCs, equating to the use a 0.6 SD criteria in sequential averaging. The 0.25 SD criterion has been criticised for being too conservative (Hamill & McNiven, 1990; James et al., 2007), alternatively this could be viewed as more rigorous; again the decision is arbitrary. Our approach has been to opt for a more conservative approach, recommending a minimum of 20 consecutive ground contacts be recorded. Moreover, we recommend that future studies perform, and report, their own sequential averaging for further consistency within motion capture research.

Conclusion:

This study found a similar number of strides were required to achieve a stable stride count across the three joints and planes of motion during treadmill running. Furthermore, this value did not change with the intensity of run, or between the beginning or end of the run. We therefore recommend the use of the upper 95% confidence interval value of 20 strides found in this study as an initial guideline for examining kinematic and spatiotemporal variables during treadmill running.

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Table 1.

Descriptive characteristics of participants, training runs, speeds, durations, $\dot{v}o_2$max, speed at lactate turnpoint (sLTP), percentage of $\dot{v}o_2$max at sLTP (%$\dot{v}o_2$), represented as mean ± standard deviation

	Female (*n* = 10)	Male (*n* = 10)
Age (years)	42.2 ± 4.0	43.8 ± 4
Height (cm)	164.6 ± 6.0	181.2 ± 7.9
Mass (kg)	58.5 ± 6.2	77.3 ± 6.5
HIIT Speed ($m.s^{-1}$)	3.9 ± 0.3	4.6 ± 0.3
HIIT rep duration (min:sec)	03:24 ± 13(s)	02:47 ± 16(s)
MICR Speed ($m.s^{-1}$)	3.3 ± 0.2	3.6 ± 0.4
MICR duration (min:sec)	32:15 ± 02:01	25:53 ± 03:40
$\dot{v}o_2$ max ($ml.kg^{-1}.min^{-1}$)	53.6 ± 5.4	60.5 ± 4.4
sLTP ($m.s^{-1}$)	3.3 ± 0.2	3.7 ± 0.4
% $\dot{v}o_2$ max at LTP	81.4 ± 5.5	72.7 ± 8.1

Table 2. Stride counts presented as mean ± standard deviation (SD) and 95% upper limit confidence (U95% CI) at foot strike (FS), maximum angle (Max), and range of motion (RoM); for the ankle joint in the three planes of motion. At beginning and end of two run-types of high intensity interval training run (HIIT) and medium intensity continuous run (MICR).

		Frontal		Sagittal		Transverse	
		Mean ± SD	U95% CI	Mean ± SD	U95% CI	Mean ± SD	U95% CI
Ankle $_{FS}$							
	HIIT start	17 ± 7	21	15 ± 8	19	16 ± 7	19
	HIIT end	15 ± 7	20	14 ± 6	16	14 ± 6	16
	MICR start	16 ± 7	20	14 ± 6	17	15 ± 6	18
	MICR end	17 ± 7	21	14 ± 7	17	14 ± 6	17
Ankle $_{Max}$							
	HIIT start	13 ± 8	18	16 ± 7	19	15 ± 8	19
	HIIT end	14 ± 6	18	15 ± 7	18	13 ± 5	15
	MICR start	14 ± 6	17	16 ± 8	19	16 ± 6	18
	MICR end	12 ± 7	17	13 ± 7	16	15 ± 7	18
Ankle $_{RoM}$							
	HIIT start	15 ± 8	19	17 ± 7	21	14 ± 7	17
	HIIT end	15 ± 7	20	14 ± 6	17	14 ± 6	17
	MICR start	15 ± 6	18	16 ± 6	19	15 ± 7	18
	MICR end	16 ± 6	20	15 ± 7	18	16 ± 6	19

Table 3. Stride counts presented as mean ± standard deviation (SD) and 95% upper limit confidence (U95% CI) at foot strike (FS), maximum angle (Max), and range of motion (RoM); for the knee joint in the three planes of motion. At beginning and end of two run-types of high intensity interval training run (HIIT) and medium intensity continuous run (MICR).

		Frontal		Sagittal		Transverse	
		Mean ± SD	U95% CI	Mean ± SD	U95% CI	Mean ± SD	U95% CI
Knee $_{FS}$							
	HIIT $_{start}$	17 ± 7	21	17 ± 6	20	16 ± 7	20
	HIIT $_{end}$	15 ± 7	19	15 ± 6	17	14 ± 6	17
	MICR $_{start}$	16 ± 6	19	14 ± 6	16	15 ± 7	18
	MICR $_{end}$	16 ± 6	20	14 ± 7	17	15 ± 8	19
Knee $_{Max}$							
	HIIT $_{start}$	15 ± 7	19	15 ± 7	18	15 ± 8	20
	HIIT $_{end}$	14 ± 6	18	14 ± 5	16	15 ± 6	17
	MICR $_{start}$	13 ± 6	17	12 ± 6	15	13 ± 6	16
	MICR $_{end}$	16 ± 6	20	14 ± 9	18	15 ± 6	18
Knee $_{RoM}$							
	HIIT $_{start}$	16 ± 7	21	15 ± 7	18	15 ± 6	18
	HIIT $_{end}$	15 ± 7	20	13 ± 7	16	12 ± 6	15
	MICR $_{start}$	15 ± 7	20	16 ± 7	20	16 ± 7	19
	MICR $_{end}$	15 ± 6	18	15 ± 7	18	15 ± 7	18

Table 4. Stride counts presented as mean ± standard deviation (SD) and 95% upper limit confidence (U95% CI) at foot strike (FS), maximum angle (Max), and range of motion (RoM); for the hip joint in the three planes of motion. At beginning and end of two run-types of high intensity interval training run (HIIT) and medium intensity continuous run (MICR).

		Frontal		Sagittal		Transverse	
		Mean ± SD	U95% CI	Mean ± SD	U95% CI	Mean ± SD	U95% CI
Hip $_{FS}$							
	HIIT $_{start}$	14 ± 8	18	17 ± 6	20	16 ± 7	19
	HIIT $_{end}$	15 ± 6	20	12 ± 6	14	15 ± 6	18
	MICR $_{start}$	14 ± 7	18	16 ± 8	19	12 ± 5	14
	MICR $_{end}$	16 ± 6	20	13 ± 5	15	16 ± 5	18
Hip $_{Max}$							
	HIIT $_{start}$	14 ± 8	19	19 ± 5	21	14 ± 6	17
	HIIT $_{end}$	15 ± 6	20	15 ± 6	18	14 ± 5	16
	MICR $_{start}$	16 ± 6	20	13 ± 8	16	16 ± 7	19
	MICR $_{end}$	16 ± 6	19	15 ± 6	18	14 ± 6	17
Hip $_{RoM}$							
	HIIT start	16 ± 7	20	15 ± 7	18	14 ± 5	16
	HIIT $_{end}$	14 ± 7	18	14 ± 6	17	13 ± 7	16
	MICR start	16 ± 7	20	15 ± 8	19	14 ± 7	17
	MICR $_{end}$	15 ± 6	18	16 ± 7	19	14 ± 5	16

Table 5. Stride Count for spatiotemporal variables represented as mean ± Standard deviation (SD) and upper 95% confidence interval (U95% CI) for Stride Frequency (SF) and Contact Time (CT).

SF		Mean ± SD	U95% CI	CT		Mean ± SD	U95% CI
	$HIIT_{start}$	13 ± 6	16		$HIIT_{start}$	16 ± 7	20
	$HIIT_{end}$	14 ± 7	18		$HIIT_{end}$	17 ± 6	20
	$MICR_{start}$	12 ± 7	16		$MICR_{start}$	16 ± 6	20
	$MICR_{end}$	14 ± 7	18		$MICR_{end}$	17 ± 7	21

Figure 1. Stride counts presented as 95% upper limit confidence interval at foot strike (FS), maximum angle (Max), and range of motion (RoM); for the ankle, knee, and hip joints in the three planes of motion. At beginning and end of two run-types of high intensity interval training run (HIIT) and medium intensity continuous run (MICR).

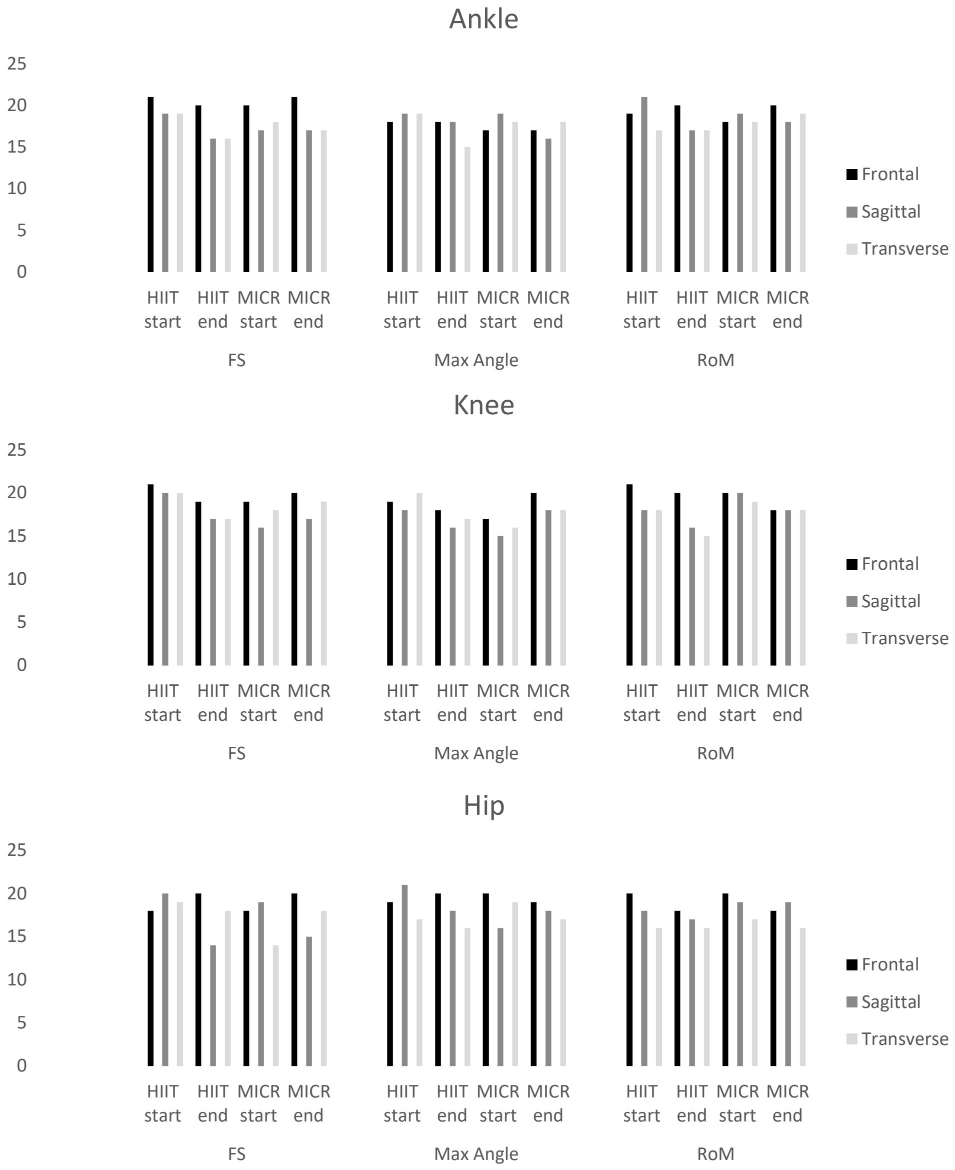

Figure 2. Stride counts presented as 95% upper limit confidence interval for spatiotemporal variables of Stride frequency and Contact Time.