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original article

Relationship between running kinematic changes and time limit at vVO_{2max}

Relação entre modificações cinemáticas da corrida e o tempo limite na $vVO_{2máx}$

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Abstract – Exhaustive running at maximal oxygen uptake velocity (vVO_{2max}) can alter running kinematic parameters and increase energy cost along the time. The aims of the present study were to compare characteristics of ankle and knee kinematics during running at vVO_{2max} and to verify the relationship between changes in kinematic variables and time limit (Tlim). Eleven male volunteers, recreational players of team sports, performed an incremental running test until volitional exhaustion to determine vVO_{2max} and a constant velocity test at vVO_{2max}. Subjects were filmed continuously from the left sagittal plane at 210 Hz for further kinematic analysis. The maximal plantar flexion during swing ($p<0.01$) was the only variable that increased significantly from beginning to end of the run. Increase in ankle angle at contact was the only variable related to Tlim ($r=0.64$; $p=0.035$) and explained 34% of the performance in the test. These findings suggest that the individuals under study maintained a stable running style at vVO_{2max} and that increase in plantar flexion explained the performance in this test when it was applied in non-runners.

Key words: Kinematics; Running; vVO_{2max}

Resumo – *A corrida realizada na velocidade do consumo máximo de oxigênio ($vVO_{2máx}$)pode ocasionar modificações nos parâmetros cinemáticos e assim, aumentar o custo energético ao longo do tempo.O objetivo do presente estudo foi analisar características cinemáticas da articulação do tornozelo e joelho durante a corrida na $vVO_{2máx}$ e a relação entre modificações cinemáticas e o tempo limite na $vVO_{2máx}$(Tlim). Onze voluntários ativos fisicamente foram submetidos a um teste incremental de corrida para determinar a $vVO_{2máx}$ e posteriormente, a um teste de velocidade constante na $vVO_{2máx}$. As variáveis cinemáticas foram adquiridas através de filmagem bidimensional a 210Hz no plano sagital esquerdo, no estágio inicial e final da corrida.De todas as variáveis angulares analisadas, a máxima plantiflexão no balanço ($p<0.01$) foi a única que aumentou significativamente entre o início e o final da corrida. O aumento no ângulo do tornozelo no contato foi correlacionado ao Tlim ($r=0,64$; $p=0,035$) e explicou 34% do desempenho no teste. Esses achados sugerem que os sujeitos mantêm um estilo de corrida relativamente estável na $vVO_{2máx}$ e que o aumento da plantiflexão no contato foi capaz de explicar o desempenho neste teste entre sujeitos não corredores.*

Palavras-chave: *Cinemática; Corrida; $vVO_{2máx}$.*

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INTRODUCTION

Kinematic analysis of exhaustive running (prolonged submaximal running and short and medium-duration running at high intensity) becomes important due to possible changes in stride pattern[1]. This fact is related to the continuous increase in blood lactate [La] and to metabolite accumulation in muscle fibers at intensities corresponding to heavy and severe domains[2], which would cause kinematic changes in the stride cycle[3].

The lower limbs have the role of absorbing energy by means of eccentrically controlled dorsiflexion[4] and knee flexion[3] at landing. Elliot and Ackland[5] highlighted the importance of the ankle joint by reporting that foot biomechanical parameters may have the major influence on running biomechanical characteristics and on the performance in a 10-km race. Fatigue could cause an imbalance in dorsiflexor and plantar flexor muscles, increasing leg impact acceleration and becoming a risk factor for injuries[6]. Other authors reported that ankle muscle fatigue caused decreased dorsiflexion at foot contact with the ground[7] and that changes in ankle angle explained 67% of the variance in oxygen uptake (VO_2) during running performed after long-duration cycling exercise[8]. Similarly, the knee joint would have a key role both in shock absorption[3] and running energy cost[9].

It is well-known that training sessions to increase VO_{2max} should be performed at velocities close or corresponding (vVO_{2max}) to this physiological index[10]. Therefore, it is interesting for sport science researchers and for trainers for some running competitions to understand the physiological and biomechanical mechanisms that may influence the time during which vVO_{2max} can be sustained. For instance, in running competitions such as 800- and 1500-m races, the required VO_2 is close to or above VO_{2max}[11]; furthermore, Tlim and vVO_{2max} were associated with performance at distances from 1500 meters to Marathon[12,13].

In order to study the great variability in Tlim among individuals, Ribeiro et al.[14] analyzed cardiorespiratory (VO_{2max}, vVO_{2max}, running economy, and ventilatory threshold) and neuromuscular (isotonic strength, velocity at maximal anaerobic running test, and vertical jump) variables and demonstrated that none of these variables could explain such variability. Gazeau et al.[15] investigated biomechanical variables and, based on the results of their research, stated that runners who maintained more stable running styles were able to increase Tlim. Hayes et al.[16] showed strong negative correlations between local muscle resistance of flexors and extensors of the hip and knee and the kinematic changes (Δ) in vVO_{2max} that occur between the beginning and the end of the run, which reveals that runners with higher local muscle resistance had less changes in kinematic variables during the run.

Thus, a void in the literature is noted, because the kinematic parameters of the ankle joint were not analyzed in the few studies that aimed to investigate kinematic changes and Tlim, which focused on the hip and the knee. Assuming that kinematic changes in the entire lower extremity are caused by muscle fatigue and that they can influence running performance, the aims of the present study were to compare characteristics of ankle and knee kinematics during running at vVO_{2max} and to investigate the relationship between kinematic changes and Tlim.

METHODOLOGY

Subjects

The study included eleven physically active male volunteers, recreational athletes who played team sports such as soccer, indoor soccer, and handball for 12 years, on average, and who had no previous experience in running on a treadmill. Mean and standard deviation for age, body mass, height, and body fat percentage were 23.17 (3.17) years, 71.7 (6.2) kg, 173.9 (5.5) cm, and 9.4 (2.9)% respectively. Before the beginning of the procedures, all volunteers signed a free and informed consent form providing information on the study, which was approved by the Ethics Committee for Research involving Human Beings at Universidade do Estado de Santa Catarina, protocol no. 27/2010.

Determination of vVO_{2max}

VVO_{2max} was determined by an incremental protocol on a treadmill, with an initial velocity of 8.3 $km.h^{-1}$ (1% slope) and increments in velocity every 3 minutes (9.3$km.h^{-1}$; 10.4 $km.h^{-1}$; 11.6 $km.h^{-1}$; 12.6 $km.h^{-1}$; 13.7 $km.h^{-1}$; 14.7 $km.h^{-1}$; 15.7 $km.h^{-1}$;16.8 $km.h^{-1}$; 17.8 $km.h^{-1}$) until volitional exhaustion. VO_{2max} was considered the highest recorded value from means calculated every 15 seconds[17]. VVO_{2max} was considered the minimum velocity in which VO_{2max} was reached and sustained for at least 1 minute. If VO_{2max} was not maintained for 1 minute, the velocity from the preceding stage was considered the vVO_{2max}[17].

Determination of Tlim

After the incremental test, new visits took place 48 hours after the first one, for running tests at 100% of vVO_{2max}. Subjects performed a warm-up consisting of a 5-minute run on the treadmill at 60% of vVO_{2max}[17]. At the end of the warm-up, they rested their feet outside the treadmill belt and were verbally informed about the test procedures. Subjects began running at lower velocities until reaching vVO_{2max}, for a period of less than 30 seconds on average. The Tlim was considered the time interval between the moment when the treadmill reached vVO_{2max} and the moment when the individual volitionally stopped the test. During both tests, subjects were verbally encouraged by the evaluators until volitional exhaustion.

Acquisition of kinematic data

Kinematic variables were obtained by two-dimensional filming from the moment the participant reached vVO_{2max} until exhaustion. A filming camera (CASIO® *High SpeedExlim* Model EX-FH20) with acquisition frequency of 210 Hz was used at 2.30 m of distance from the treadmill and 1.0 m above the ground level. Eight joint reflective markers (5th metatarsal, lateral border of the calcaneus, lateral malleolus, lateral epicondyle of the knee, greater trochanter of the femur, greater tubercle of the humerus, lateral epicondyle of the humerus, and styloid process of the ulna) were fixed at the left side of the body directly onto the skin after shaving and alcohol cleaning.

For the purpose of comparative analysis, data were collected at two time-points: a) beginning: first foot contact with the ground 20 seconds after the subject reached vVO_{2max}; b) final: the moment when the 5 strides of interest precede 10 seconds to the end of the test. In each of the moments, five full stride cycles were analyzed. A stride cycle was considered the interval between two successive contacts of the calcaneus of a same foot with the ground.

Studies with a similar design used cycles of 1 stride[18], 3 strides[16], and 5 strides[7]. Authors showed that there is great validity (r=0.96) between strides in relation to temporal and kinematic variables for male runners[19] and that, even among not highly trained runners, the reproducibility of kinematic parameters (hip and knee angles) was high[20].

To determine ankle angle in neutral position, video imaging of the subject in upright position with no treadmill slope was obtained. We considered the angle formed between the segment feet (defined from 5th metatarsal and lateral malleolus markers) and the segment leg (defined from lateral malleolus and lateral epicondyle of the femur markers). For reference, ankle angle in neutral position was considered to be 0° (angles greater than 0° indicate dorsiflexion and angles less than 0° indicates plantar flexion)[7]. Knee values were estimated on the basis of Knee Supplementary Angle: 180° minus knee internal angle[7].

As for the filming area, a square-shaped calibrator with 4 m^2 was used, manufactured with white pipes and tubes of polyvinyl chloride (PVC). The vertices of this square were marked with black insulating tape to contrast with the material from the pipes and tubes and to be used as a reference for measuring the sides of the calibrator.

The videos were exported to the Ariel Performance Analysis System (APAS) software and then the process of semi-automated digitalization began. A model for digitalizing the 8 marker points was created, followed by the formulation of a two-dimensional calibration model with X and Y coordinates. After the formulation of the model and the digitalization, the marker points were transformed by the APAS software using the DLT *(Direct Linear Transformation)* method and filtered with a 4th order *Butterworth* filter with a cutoff frequency of 6 Hz, in an attempt of eliminating any possible noise, instrument failure or digitalization errors.

Angular displacement values were calculated by the APAS software and, for analysis purposes, mean kinematic values for the 5 strides of interest from each running stage were used. The kinematic variables of interest were: ankle angle at initial contact (AAC), maximal dorsiflexion during stance (MDS), ankle angle at toe-off (AAT), maximal plantar flexion during swing (MPFS), ankle range of motion (ARM), knee range of motion (KRM) – both ranges defined as the difference between the higher and the lower angle recorded during the stride cycle –, knee angle at initial contact (KAC), maximal knee flexion angle during stance (MKFSt), maximal knee flexion angle during swing (MKFSw), knee extension angle at toe-off (KET). The kinematic changes between the beginning and the end of the running exercise were computed as the difference between initial and final values and expressed in absolute values.

Statistical Treatment

After the normal distribution of data (*Shapiro-Wilk* test) was confirmed, the t-Student test was applied to compare angular variables from the beginning and the end of the run. Cohen's *d* effect size was used for a better practical description. Effect size values (d) were classified as: 0.0 to 0.19 = trivial; 0.20 to 0.59 = small; 0.60 to 1.19 = moderate; 1.20 to 1.99 = large; 2.00 to 4.00 = very large[21]. The relationship between kinematic changes and Tlim was tested using the Pearson correlation test. A regression analysis (enter method) was applied to ascertain the contribution of kinematic changes to Tlim. To do so, variables that presented significance level for the correlation between kinetic changes and Tlim below 0.25 were selected, because this condition can result in variables with high relationship power[22]. The significance level was set at $p<0.05$.

RESULTS

Mean results for the group that performed the progressive and continuous tests are shown in table 1.

Table 1. Physiological indices derived from incremental and continuous tests.

Variable	Mean±SD
VO_{2max} (ml.kg^{-1}.min^{-1})	54.04±4.66
vVO_{2max} (km.h^{-1})	15.40±1.50
Tlim (s)	404±111

VO_{2max}: maximal oxygen uptake (VO_{2max}); vVO_{2max}: maximal oxygen uptake velocity; Tlim: time limit at vVO_{2max}.

The comparison of mean values for the kinematic variables between initial (I) and final (F) running stages at Tlim is shown in table 2.

Based on the comparisons presented in table 2, it was possible to observe that maximal plantar flexion during swing was the only variable that increased significantly ($p<0.01$), and that none of the knee angles showed significant difference between the beginning and the end of the run. Angular values (mean for the group) for ankle and knee along the stride cycle are expressed in figure 1A and 1B respectively.

It is possible to notice a superposition of values from the initial contact to the end of the stance phase and toe-off (between 1 and 40% of the cycle) with higher plantar flexion during swing at the end of the run (between 40 and 100% of the cycle). Knee values were superposed from initial contact to near toe-off (~28% of the cycle), and also at knee extension – propulsion phase – (between 28 and 35% of the cycle), at maximal flexion during swing (between 64 and 71% of the cycle), and during the preparation for the next contact with the ground (71 to 100% of the cycle).

Table 2. Comparison of kinematic variables between the beginning and the end of the run

Variable		(Mean±SD)	(%)	t	p	d
Ankle angle at initial contact - AAC (º)	I F	5.81±2.07 5.13±4.78	11.7	0.700	0.500	0.32 Small
Ankle angle at toe-off - AAT (º)	I F	-19.23±5.07 -18.95±5.76	1.5	-0.315	0.759	0.05 Trivial
Maximal dorsiflexion during stance - MDS (º)	I F	26.23±4.69 26.78±5.64	2.0	-0.649	0.531	0.11 Trivial
Maximal plantar flexion during swing - MPFS (º)	I F	-24.03±7.32 -25.79±7.67	7.1	3.143	0.009*	0.25 Small
Ankle range of motion - AROM (º)	I F	50.81±7.22 52.71±6.45	3.6	-1.796	0.103	0.26 Small
Knee angle at initial contact - KAC (º)	I F	20.40±5.03 20.49±5.04	0.4	-0.064	0.950	0.01 Small
Maximal knee flexion angle of during stance - MKFSt (º)	I F	48.18±6.10 48.60±4.91	0.8	-0.336	0.744	0.06 Trivial
Knee angle at toe-off - KAT (º)	I F	18.09±6.67 17.04±6.86	5.8	1.301	0.222	0.15 Trivial
Maximal knee flexion angle during swing - MKFSw (º)	I F	108.67±9.27 110.73±9.43	1.8	-1.696	0.121	0.22 Small
Knee range of motion - KROM (º)	I F	90.58±11.51 93.68±12.42	3.3	-2.205	0.052	0.26 Small

%: percentage differences; t: t-Student values; p: significance; *d*: Cohen's effect size; *p ≤ 0.01; I: initial stage; F: final stage

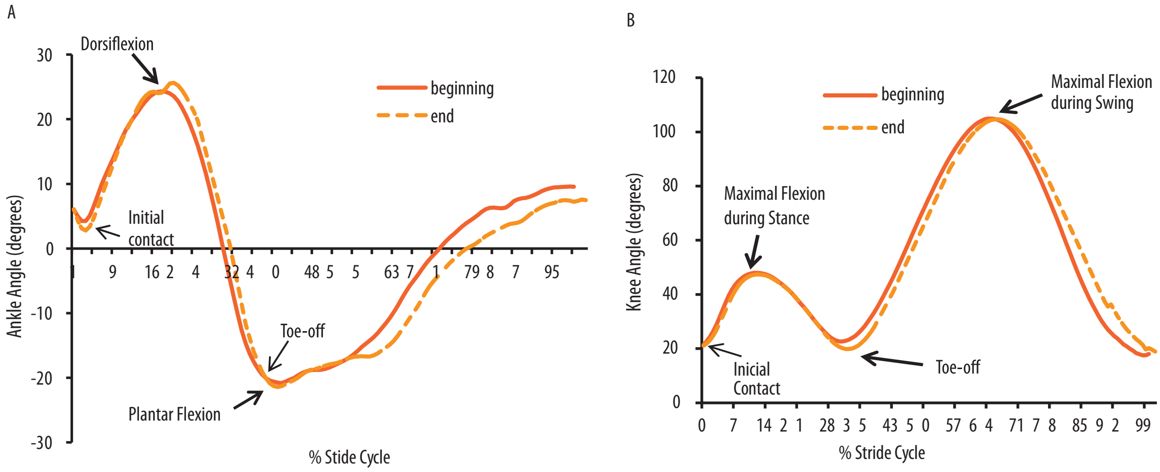

Figure 1. Angular values for ankle (A) and knee (B) along the stride cycle at the beginning and the end of the test.

The results for the correlation tests between kinematic changes and Tlim are shown in table 3.

Table 3. Correlation coefficients between kinematic changes (Δ) and Tlim.

Correlation	r	ρ
ΔAAC x Tlim	0.64	0.035^{a**}
ΔMDS x Tlim	0.03	0.993
ΔKAT x Tlim	-0.19	0.558
ΔMPFS x Tlim	-0.03	0.365
ΔAROM x Tlim	-0.23	0.487
ΔKAC x Tlim	-0.47	0.142^{a}
ΔMKFSt x Tlim	-0.37	0.273
ΔKAT x Tlim	-0.20	0.563
ΔMKFSw x Tlim	-0.45	0.169^{a}
ΔKROM x Tlim	-0.27	0.414

Tlim: Time limit at vVO$_{2max}$; **Significant difference $p<0.05$; ^{a}Variables included in multiple regression.

Based on the results for the correlation test presented in table 3, it is noticed that the change in ankle angle at contact was the only variable that showed a significant positive correlation with Tlim.

Table 4 presents the variables that had a prediction ability with Tlim. It can be observed that the increase in ankle angle at contact explains 34% of the performance in the test. However, when it was analyzed together with the changes in knee angle at contact and maximal knee flexion during swing, its predictive power was not significant.

Table 4. Multiple regression for selected kinematic changes, considering Tlim as the dependent variable.

	Independent Variable	Adjusted R^2	p
Tlim	ΔAAC	0.34	0.035*
	ΔAAC + ΔKAC	0.35	0.074
	ΔAAC + ΔKAC + ΔMKFSw	0.37	0.107

*$p<0.05$

DISCUSSION

The aims of present study were to compare kinematic characteristics between the beginning and the end of the run at vVO$_{2max}$ and to investigate the relationship between kinematic changes and Tlim. It was demonstrated that a) maximal plantar flexion during swing was the only variable to increase significantly; and b) the increase in ankle angle at contact was related to Tlim and explained 34% of the performance in the test.

The increase in maximal plantar flexion during swing corroborates the findings of Kellis and Liassou[7]. In fact, dorsiflexor and plantar flexor muscles affect foot position not only at contact but also during toe-off and swing[4,22]. Accordingly, an increase in gastrocnemius activity was observed during swing with plantar flexor fatigue[7], which may explain the higher plantar flexion during swing found also in the present study. However, these findings warrant caution, because the percentage difference was small (7%), as well as that for all other study variables. Additionally, the effect size, which measures the difference between means in terms of standard deviation units (d=0.24), was also considered small. The use of this measuring tool is an attempt of replacing the concept of statistical significance with more useful notions of practical significance. Thus, if we link the results of the present study with those of other authors who consider a difference below two degrees in ankle and knee angles during the run to be insignificant[8], it can be inferred that these changes are not relevant.

The ankle angle at initial contact, stance and toe-off did not change between the beginning and the end of the run. On the other hand, Christina et al.[4] and Kellis and Liassou[7] showed that dorsiflexion at contact decreased after a fatigue protocol of dorsiflexor and plantar flexor muscles. Increased dorsiflexion during contact reduces energy conversion from translational to rotational, because most of the energy is lost at collision with the ground. Therefore, landing with less dorsiflexion can improve storage and conversion of elastic energy[23].

Based on these assumptions, one have an explanation for the fact that the change in ankle angle at contact was the only variable that showed a significant positive correlation with Tlim ($r=0.64$; $p<0.05$) and explained 34% of Tlim. Thus, it is inferred that increasing plantar flexion at foot strike with the ground can improve the performance in the test. Similarly, Bonacci et al.[8] showed that changes in ankle angle at contact explained 67% of the variance in VO_2 when triathletes performed a submaximal running after a 45-minute cycling exercise. In fact, plantar flexion position at initial contact can be more effective, reducing stance time, because rotational energy is transferred more effectively[23], which improves running economy[8]. Although the difference in ankle angle at contact between the beginning and the end of the run was not significant in the present study, it was the variable that showed the highest percentage variation (7%) and the highest effect size ($d=0.32$).

The knee angle did not show significant differences in any phase of the cycle, which corroborates with Heyes et al.[15], who analyzed sub-elite runners at vVO_{2max}, but is opposed to several studies that investigated the effects of fatigue on knee angle at contact and maximal knee flexion during stance in submaximal running[1,7,24], in which subjects increased flexion. The higher flexion at initial contact reduces the likelihood of injuries due to the lower reaction force of the ground and the better shock absorption[18,24]. Moreover, the stretching-shortening cycle has the role of improving the ability of producing force during the final phase (concentric action). It is inferred that the less economic running is related to a more complacent running style (less vertical stiffness), which can be represented by a higher knee flexion and a delay in the transition from stretching to subsequent shortening[25]. In the fatigue state, changes in the ground reaction force are associated with difficulties in maintaining angular displacements constant, and the reduction in force after the impact is probably related to a higher knee flexion[26]. A consequence of this process would be that, in order to keep the same performance for the stretching-shortening cycle at a given running velocity, the individual must perform a higher muscle workload during the propulsion phase, causing a higher fatigue progression[26]. Valiant[9] estimated an increase of 25% in VO_2 for every 5° of increase in maximal knee flexion during stance, which leads one to believe that this angle determines the metabolic cost associated with shock attenuation. In this case, as with knee angle at contact, the subjects of the present study may have maintained maximal knee flexion during stance as an attempt to avoid an increase in metabolic cost during the final stages, even with impaired shock attenuation

The study presented some technical limitations, such as the recruitment of non-runners individuals with no experience in running on a treadmill and the fact that motion analysis was limited to the sagittal plane. In this case, differences in running economy between treadmill and track seems to exist, due to runner's inexperience on the treadmill, which could lead to imbalances and changes in running technique and a possible variation in velocity on the treadmill from foot contact with the walking belt[27].

Furthermore, the ankle moves in the three planes of motion, and it is well-known that the rotation axis of this joint is not perpendicular to the sagittal plane. Thus, it bears stressing that the two-dimensional measure can be limited in comparison with the three-dimensional measure. Foot pronation, dorsiflexion and abduction occur in the frontal, sagittal and transverse planes respectively. There is a causal relationship between hyperpronation and excessive use injuries, because pronation is necessary to attenuate impact forces[28]. Therefore, in situations of muscle fatigue, it would be interesting to analyze foot pronation angle as well, for a better discussion on motion in the sagittal plane and on the relationship with the performance in the test.

CONCLUSIONS

It can be concluded that, during running at vVO_{2max}, subjects maintain a relative stable running style, because no difference with practical significance was observed between the beginning and the end of the run. Increasing ankle plantar flexion at contact during the test might have some beneficial effect on prolonging Tlim and could thus explain the performance in the test among non-runners subjects.

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