Stride smoothness evaluation of runners and other athletes

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Abstract

The purpose of this study was to compare an objective measurement of smoothness between a group of runners and a group of non-runners during running and fast walking. Smoothness was quantified by evaluating the endpoint jerk-cost (JC) at the heel. Subjects walked at a speed of 1.75 m·s \(^{-1}\) and ran at a speed of 3.35 m·s \(^{-1}\) on a motor driven treadmill while 2-D kinematic data (60 Hz) were collected from a sagittal plane view. The runners were found to be smoother than the non-runners during both gait conditions, suggesting that this group was inherently smoother in gait related tasks. This study demonstrated that the smoothness of gait can be quantified objectively by evaluating the end-point JC at the heel, and that competitive runners tend to exhibit smoother strides than recreational runners during both running and fast walking. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Even to a casual observer, it is apparent that the running stride of an elite level runner typically exhibits qualities that are not evident in the stride of a recreational runner. Among the stride characteristics cited by coaches and other observers when differentiating between the running strides of elite and recreational runners is the degree of smoothness. It is generally agreed that elite runners are smoother than their recreational counterparts, although this subjective evaluation does not appear to be based upon any substantive or objective evidence.

When observing various skilled movement tasks, Winston and Schmidt [1] have concluded that differences in smoothness are relatively easy for an observer to recognize. Although these authors [1] do not suggest any objective method of assessing smoothness, several other researchers [2–5] have conducted studies in which an objective evaluation of smoothness was made. In all of these studies, a quantitative measurement of smoothness was utilized to demonstrate that smoothness of simple, novel, movements increased as the skill level of the task improved, or became better learned. These researchers quantified smoothness by evaluating the jerk-cost (JC) function, defined as:

\[
JC = \int_0^T \left( \frac{d^3r}{dt^3} \right)^2 dt
\]  

(1)

where \( T \) is the total movement time, and \( r \) is the position vector of a limb segment. When utilizing this function to evaluate smoothness of complex multi-joint movements, it has been demonstrated \([6–8]\) that the position vector, \( r \), is best represented in terms of endpoint Cartesian coordinates.

The original theory of maximum smoothness (minimum jerk) suggested that the trajectory of a movement endpoint is planned in a manner that would minimize the JC function \([9]\). In gait, this endpoint may be best represented by the foot. It has been suggested \([10]\) that maximizing smoothness is 'likely to be very important for the path of the object of greatest attention for the CNS' (p. 139), and that 'during walking and running the objects of greatest attention for the CNS are movements of the feet' (p. 181). Winter \([11]\) concurred that a smooth foot trajectory is important during gait. One of the major motor functions during the gait cycle, as stated by Winter \([11], p. 2,\) is the “control of foot trajectory to achieve safe ground clearance and a gentle heel or toe landing”. The importance of foot placement is also demonstrated in a number of sporting activities.

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in which there are boundaries, such as football, basketball, and some track events. In these cases, athletes often maintain a consistent running stride while avoiding the boundary, apparently without direct visual feedback. In a study which examined a number of possible endpoints, Hreljac and Martin [12] established that the best choice of a movement endpoint during gait was the position of the heel.

Although the JC function was originally formulated as a minimizing criterion for the planning of single joint movements, then extended to multi-joint movements, this does not imply that movements of the heel are optimally smooth during gait. However, the movements are likely planned to be as smooth as possible within the physiological constraints of the system. The level of success in translating from the planning stage to the execution stage of the movement would then determine the degree of smoothness exhibited, which could subsequently be evaluated by the mathematical expression of JC.

During the acquisition of novel skills of the upper body [4] and lower body [2], it has been demonstrated that the smoothness (as measured by JC) of a movement increases in a logarithmic fashion as the number of trials increases, reaching a limit within a relatively small number of trials (< 100) in a similar manner that skill level improves during the learning of novel tasks [13]. For overlearned motor skills such as walking and running, it can be assumed that the limit of smoothness of the movement has been achieved by adulthood, and that few changes in the level of smoothness would occur during adulthood in the absence of gait modification for reasons such as injury or performance enhancement. If it can be assumed that the skill level of elite runners is greater than that of recreational runners, then it can be hypothesized that the level of smoothness of the movement will also be greater. The primary purpose of this study was to compare an objective measurement of smoothness (JC) during running between a group of competitive runners and a group of non-running athletes. A secondary purpose of the study was to compare smoothness between the groups in another related task (fast walking) in which neither group would possess a training advantage, to determine whether differences in smoothness were inherent or related to other factors such as training. The smoothness of walking and running was assessed by evaluating the endpoint JC function at the heel for three consecutive strides.

2. Methods

2.1. Subjects

Two groups of 12 well-trained ($\dot{V}O_{2\text{max}} = 57.6 \pm 8.0 \text{ ml kg}^{-1}\text{min}^{-1}$), young athletes (age = 25.8 ± 4.0 years) were subjects in this study. One group (R) consisted of middle to long distance runners (six males, six females) who participated in running events on a competitive basis, while the second group (NR) was comprised of non-runners (six males, six females) who were participants in a variety of sports and activities, including hockey, tennis, soccer, volleyball, aerobics, and weight training. Only subjects who utilized a heel strike pattern of running were chosen as subjects. Prior to participation in the study, all subjects signed informed consent forms that reiterated the basic procedures and intent of the study, and warned of any potential risks involved as a result of participation.

2.2. Experimental procedures

During the experimental sessions, subjects either walked (1.75 m s$^{-1}$) or ran (3.35 m s$^{-1}$) on a motor driven treadmill. Treadmill speed was validated by a photocell timer, activated for 10 treadmill revolutions. Subjects who were unfamiliar with treadmill locomotion were habituated by walking and running at a variety of speeds for a period of at least 15 min prior to data collection. This length of habituation was determined to be sufficient to reduce variability in kinematic variables by previous researchers [14–17]. It should be noted that some authors [18,19] have found slight differences between treadmill and overground locomotion in selected temporal and kinematic parameters while others [20] have reported no significant differences. Despite possible differences existing between treadmill and overground locomotion, a treadmill was utilized during this study due to practical considerations. It was felt that subjects would be more likely to maintain a consistent stride after 5 min of treadmill walking or running than if they were to run (or walk) down a relatively short laboratory runway.

Subjects walked or ran at the experimental speed for at least 5 min prior to being videotaped with a single Panasonic AG-450 video camera, located approximated seven meters from the left side of subjects, set up perpendicular to the treadmill motion. Videotaped data were collected for a period of about 30 s at a frequency of 60 Hz and an exposure time of 2 ms. Reflective markers placed on the lateral aspect of the heel of each subject’s left shoe just above the midsole were digitized for three complete consecutive strides (randomly selected), to record the motion of the heel in the sagittal plane. An additional 30 frames of data were digitized before the first stride and after the third stride to accommodate subsequent data smoothing procedures.
2.3. Data reduction

After digitizing, coordinate data were smoothed using a fourth order, zero-lag Butterworth filter. Optimal cutoff frequencies were used for smoothing of the horizontal and vertical (x and y) components of the heel marker were determined using the residual method of Wells and Winter [21]. First and second derivatives (velocity and acceleration) were calculated using finite difference equations. Acceleration data were then smoothed using new cut-off frequencies prior to calculating the first derivative of acceleration (jerk). The original cut-off frequencies chosen were 5.0 Hz for the horizontal component, and 4.5 Hz for the vertical component. These values are similar to the value of 4.8 Hz recommended during running by Winter et al. [22]. The second set of cut-off frequencies were 7.5 and 6.5 Hz for the horizontal and vertical components, respectively.

Since the smoothing and differentiation technique chosen could have a profound effect on the calculation of JC, several data smoothing methods were compared prior to undertaking this step. Among the techniques compared were Fourier transforms, quintic splines, and single, double, and triple applications of a digital filter. To compare these techniques, the values of a known complex function and the third derivative of the function were calculated for a range of 100 values. The input values represented time (increments of 0.0167 s to simulate data collection at 60 Hz), while the calculated value of the function represented displacement. Random noise (approximating the estimated relative error in the digitizing and reconstruction of true data) was then introduced into the calculated values. The various data smoothing methods were applied at this point, and the root mean square (RMS) deviation from the third derivative of the known function was compared between methods. In addition, various numbers of extra points were added to the beginning and end of the original data set before smoothing to determine whether endpoint smoothing problems could be alleviated. The double smoothing method described above was found to produce the lowest RMS deviation from the actual third derivative calculation provided that a minimum of 30 extra frames of data were included before and after the data frames of interest.

2.4. Data analysis

For the strides of interest, the endpoint JC of the heel marker was calculated in the horizontal (JC_x) and vertical (JC_y) directions using Eq. (1). A resultant component (JC_r) was also determined. In addition to determining values for an entire stride, JC was also calculated during the stance and swing phases of the stride. To account for variations in stride frequency and to standardize results, all JC measures were normalized in time by dividing results by the time component for the appropriate stride phase (i.e. for stance phase calculations, values were divided by stance time; by swing time for swing phase calculations; and by stride time for entire stride calculations). By doing this, all JC components were expressed as a JC m² s⁻³. A multivariate analysis of variance (MANOVA) was utilized to test for differences between groups in the mean values of the three dependent variables (JC_x, JC_y, and JC_r) during each phase of the stride for both walking and running. For all comparisons, the significance level was set at a = 0.05. The correlation coefficient between the JC_r components found in the walking and running conditions was also calculated.

3. Results

Graphs comparing the time histories of the vertical component of heel displacement, velocity, acceleration, and jerk between the groups are shown for both the walking (Fig. 1a–d) and running (Fig. 2a–d) conditions. These graphs are averaged for the 12 subjects in each group and have been included only for illustrative purposes. No statistical analyses were performed directly on the data from these graphs. The time histories of the other components (horizontal and resultant) which are not shown, demonstrated a similar pattern of differences between the groups; that is, the differences became progressively more apparent with higher derivatives.

The JC data were first analyzed to check for gender differences. If gender differences did exist, then it would not have been appropriate to use mixed gender groups in the analysis. There was no group by gender interactions, nor was there any gender main effects found for any of the independent variables during either the walking or running conditions. Thus, all subsequent analyses were based upon results obtained for the entire groups. Although no significant differences were found between groups in stance, swing, or stride time during either walking or running conditions, all results were normalized in time for standardization purposes.

During the walking condition, the R group had significantly lower values of each component of JC in all phases of the stride (Fig. 3a–c). During the running condition, all components of JC were significantly lower for the R group during the swing phase, and the entire stride, but during the stance phase, only the JC_r component exhibited a significant difference (Fig. 4a–c).

A scatterplot of the individual values for the JC_r component for the entire stride during both the running and walking conditions (Fig. 5) illustrates the distribution of values within and between the groups. The plot...
shows the values of \( J_{cr} \) during the running condition in ascending order within each group. Thus, Subject 1 in each group had the lowest \( J_{cr} \) value for the running condition, while Subject 12 of each group had the highest value. Corresponding \( J_{cr} \) values during walking for the same individual are plotted on the same graph. Similar results were noted for other components of JC and during other stride phases. This graph is considered to be representative of other components of JC and other stride phases. Differences in JC between groups were somewhat more pronounced during the running condition, although the general distribution of scores is similar. It can be seen from Fig. 5 that there was not a perfect correlation between \( J_{cr} \) values during running and walking, but there was found to be a significant, albeit weak correlation \((r = 0.47)\) between these variables.

4. Discussion

Only small differences in the vertical displacement of the heel existed between the groups during both walking (Fig. 1a) and running (Fig. 2a). The heel of the runner group appears to have ascended and descended more gradually than for the non-runners during both walking and running conditions. The differences between groups became greater with each successive derivative calculated (Fig. 1b–d and Fig. 2b–d). Although the differences between groups were quite noticeable in the third derivative (jerk) curves (Fig. 1d and Fig. 2d), the calculation of JC that was utilized during this study further ‘penalized’ high jerk values by squaring the third derivative results before integration.

It is quite obvious that the assessment of JC is a very sensitive measure, and could be greatly affected by the data smoothing method and the smoothness parameters consigned. A double data smoothing method was first utilized by Vaughn [23] who determined that when using a digital filtering technique, the acceleration could be predicted better when smoothing the velocity data (calculated using finite difference equations). In the present study, a similar double smoothing method was found to be the best of several tested in reproducing third derivative curves from displacement data in which random noise was introduced. Although the double smoothing method was utilized exclusively in all jerk calculations reported in this study, the JC calculations

Fig. 1. Average curves of the vertical component of heel (a) displacement, (b) velocity, (c) acceleration, and (d) jerk during walking for runners (R) and non-runners (NR).
and analyses were also conducted after other selected data smoothing techniques were carried out to make comparisons between methods. Whatever method was used, the relative results were always consistent. That is, subjects who had high values of JC when the double smoothing technique was carried out, also had high JC values when other data smoothing techniques were used, although the actual values varied. Thus, it would seem that although the data smoothing technique is critical in assessing true JC values, a range of data smoothing techniques would have been acceptable for comparative purposes.

It has been suggested [7] that voluntary movements are made to be as smooth as possible in the absence of any overriding concerns. This ‘minimum jerk’ theory [7,9,24] has been shown to successfully predict endpoint trajectories during simple, planar, upper limb movements in monkeys [25] and humans [6], but has been less successful in predicting the trajectory of more complex movements [2,26,27], or movements with extremes in speed [3,5,28]. Variations of the minimum jerk model [5,27,29] have only been moderately more successful in predicting the trajectory of complex movements. This is likely due to the fact that there are several different (and sometimes competing) performance objectives involved in complex movements. Although minimizing jerk may not be the only performance objective of complex movements and movements in which there is significant environmental interaction, it is still likely to be an important objective and may be minimized within the physical limitations of the system, and with consideration to other performance objectives. In addition, there are several performance objectives which could be compatible with optimizing smoothness, such as minimizing joint loading [30].

Bergmann et al. [30] have hypothesized that smooth gait patterns reduce joint loading, and thus decrease the risk of injury. Since it would definitely be beneficial for competitive runners to possess a stride which does not predispose them to injury, it is possible that a person exhibiting a generally smooth gait pattern would be more likely to choose to be a runner than a person who does not run smoothly. Presumably, the risk of injury, and the frequency and/or severity of pain in the lower limb joints would be diminished for such a person. A person who is more susceptible to being injured during a sport or activity is less likely to continue being active.
in that sport. Thus, the ‘inherent’ smoothness of the runners could possibly serve as a means of self-selection regarding participation as a competitive runner. Of course, the majority of joint loading occurs during the initial impact phase of the running stride, and it is these impact forces which are generally considered to be related to injury [31]. So, smoothness could only be a factor in injury during the stance phase, particularly during the early part of the stance phase. However, it is unlikely that a person could exhibit a ‘jerky’ movement during the swing phase only to become smooth during the stance phase. During the running condition (for all 24 subjects), there was found to be a high correlation ($r > 0.9$) between smoothness during the swing phase and smoothness during the stance phase. It is probable that any observed perception of running stride smoothness would primarily be influenced by smoothness during the swing phase, since the movement frequency is lower at this time, and thus easier for an observer to evaluate subjectively. If smoothness were an issue in injury potential, it is likely to be influenced primarily by smoothness during the initial part of the stance phase.

Since the theory of minimum jerk is based upon movement planning rather than movement execution, it can be argued that voluntary movements are generally planned to be made as smooth as possible within the physical limitations of the system and with consideration to other performance goals. However, some people will always be more successful than others in the execution of the movement. The success of the translation from movement planning to movement execution could possibly be related to the concept of movement ‘coordination’. In the present study, it was found that the group of runners were not only smoother than the...
non-runners during running, but also during fast walking as indicated by generally lower values of JC components during all phases of the stride for both conditions (Figs. 3 and 4). The lower values of JC for the runners during running was expected, and helps to confirm the subjective evaluation of differences in smoothness between the groups, while the greater smoothness demonstrated by the runners during the fast walking may indicate that the runners were inherently smoother than the non-runners in gait related tasks. It can be hypothesized that all subjects planned to make the walking and running movements to be as smooth as possible, but the runners were more successful in the execution of that plan, exhibiting a higher level of coordination in the walking and running movements.

5. Conclusions

Although this study did not identify the components that produce a smooth gait pattern, it has effectively demonstrated that the smoothness of gait can be objectively quantified by evaluating the endpoint JC at the heel. Competitive runners were found to be smoother than non-runners during running, verifying the subjective evaluation. Furthermore, the runners were also determined to be smoother during fast walking, suggesting that they were inherently smoother during gait related tasks. The muscular coordination required to produce a smooth stride and the relationship between smoothness and injury potential should be examined in follow-up studies.
References