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Accounting for elite indoor 200 m sprint results

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Times for indoor 200 m sprint races are notably worse than those for outdoor races. In addition, there is a considerable bias against competitors drawn in inside lanes (with smaller bend radii). Centripetal acceleration requirements increase average forces during sprinting around bends. These increased forces can be modulated by changes in duty factor (the proportion of stride the limb is in contact with the ground). If duty factor is increased to keep limb forces constant, and protraction time and distance travelled during stance are unchanging, bend-running speeds are reduced. Here, we use results from the 2004 Olympics and World Indoor Championships to show quantitatively that the decreased performances in indoor competition, and the bias by lane number, are consistent with this 'constant limb force' hypothesis. Even elite athletes appear constrained by limb forces.

Keywords: biomechanics; sprint; run; force

1. INTRODUCTION

Bias according to lane assignment has long been recognized in athletics (e.g. Jain 1980). This may be due to both biomechanical and psychological factors. One mechanical factor proposed as a limitation to sprint performance is the force experienced by the limbs during stance (Weyand *et al.* 2000). On running around an appropriately banked bend, sprinters effectively experience an increase in body weight (but not mass), as ground reaction forces are required both to overcome gravity and provide the centripetal acceleration (figure 1). If limb force and certain kinematic factors are constrained (see below), the increases in force requirement on sprinting around a bend result in a decrease in sprint speed, with sprints around tighter bends being slowed to greater extents.

Greene & McMahon (1979) and Greene (1985) provide an analysis of running around bends from first principles, with the goal of making as few simplifying assumptions as possible. Such an approach provides support for the constant limb force concept with data from both sprinting amateur runners (Greene 1985), and mice turning tight corners (Walter 2003): stance time, and hence duty factor (the proportion of stride time the foot spends in contact with the ground), increases on bends, and reduced sprint speeds are observed. In contrast, the constant force hypothesis fails for Greyhounds (Usherwood & Wilson 2005): Greyhounds experience greatly increased limb forces when racing around bends; duty factor and speed are not altered to compensate for the increased net force requirements.

We develop an analysis to determine whether the performance of elite human athletes trained to run around banked bends of relatively tight radii is consistent with the constant limb force hypothesis. Are Greyhounds special, or can constraints to limb force be avoided in specialized humans? Using the constant force hypothesis and two kinematic assumptions (see below) we make use of the 2004 Olympic Games as inputs to predict the results of the World Indoor Championships from the same year. This analysis is particularly timely as the indoor 200 m discipline has subsequently been abandoned by the IAAF because of the extreme bias observed according to lane assignment.

Our model is similar to previous analyses in that it is based on the assumptions that neither limb forces nor the distance travelled during stance (L_{stance}) vary with sprinting around bends of different radii. The constant L_{stance} assumption is broadly supported by a range of empirical data (Cavagna *et al.* 1976; Greene & McMahon 1979; Greene 1985; Weyand *et al.* 2000). Our model deviates subtly from that of Greene (1985) in that we assume protraction time—the time taken to swing the leg forwards (t_{swing}) between each stance period for that leg—to be constant, rather than assuming a constant stride frequency. In order to keep stride frequency constant after an increase in stance time due to sprinting around a bend, t_{swing} would have to reduce—the limb protraction velocity would have to increase. Instead, we assume that the leg is protracted at maximum velocity under all conditions, keeping t_{swing} constant and allowing stride frequency to vary slightly. While this development does add a further empirical term to the model, we feel the assumption to be more justifiable, and maximally performing sprinters of a range of standards achieve very similar values for t_{swing} (Weyand *et al.* 2000), so there is little added complexity.

2. MATERIAL AND METHODS

(a) *Model development*

The presumption behind the model (figure 1) is that duty factor alters to conserve limb forces in response to the differing acceleration requirements for sprinting around bends of different radii. If swing time and stance length are constrained, then the changes in duty factor required to maintain constant limb force during stance determine the sprint speed achievable.

The acceleration a (the mass-specific force, so the rest of the analysis does not require body masses) requirement for running around a bend of radius r at a speed v is given by:

$$a = \sqrt{g^2 + \left(\frac{v^2}{r}\right)^2} \tag{2.1}$$

(see figure 1). Note that the effects of 'heel-over' (Greene 1987) and lateral slipping (Alexander 2002) can effectively be ignored because indoor bends are appropriately banked; the acceleration vector due to the combination of gravity and centripetal acceleration is approximately perpendicular to the track surface.

Duty factor is given by:

$$\beta = \frac{t_{\text{stance}}}{t_{\text{stance}} + t_{\text{swing}}}. \tag{2.2}$$

Using the constant force assumption, and an assumption that the relevant aspect of force (likely candidates include peak force and mean force during stance) is, by conservation of momentum and a consistency in shape of the force profile, inversely proportional to

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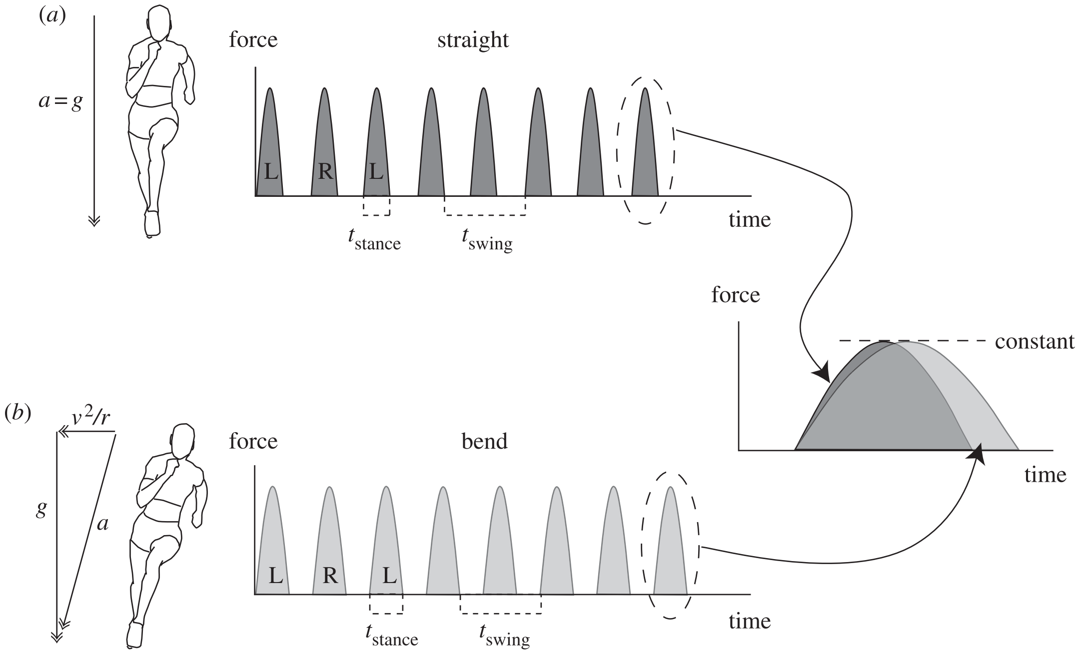

Figure 1. A representation of the modelled changes made on sprinting around a bend. When sprinting along the straight, the average forces from both left and right (L and R) legs have to be sufficient to oppose gravity (*a*, dark grey); on running around a bend (*b*, light grey), centripetal accelerations (v^2/r) add to the mean force requirements of the legs. The model presumes that this is met by increasing the proportion of time each foot spends in contact with the ground (the duty factor, $t_{\text{stance}}/(t_{\text{stance}}+t_{\text{swing}})$) instead of increasing the peak forces transmitted through the leg (see combined plot of forces during stance on right for comparison). If protraction time t_{swing} and the distance covered during stance are constrained, this increase in duty factor requires a decrease in speed.

duty factor (following principles set out in Alexander *et al.* 1979):

$$F = \text{const.} \propto \frac{a}{\beta}. \tag{2.3}$$

Therefore

$$\beta = k_\beta a, \tag{2.4}$$

where k_β is a constant that applies on straights and bends, and can be determined from 'straight' parameters, when $r=\infty$ and $a=g$:

$$k_\beta = \frac{\beta_{\text{straight}}}{g}. \tag{2.5}$$

Assuming changes in horizontal speed V during a stride are negligible, then:

$$\beta = \frac{L_{\text{stance}}}{L_{\text{stance}} + V t_{\text{swing}}}. \tag{2.6}$$

So, β_{straight} for equation (2.5) can be derived from 'straight' conditions:

$$\beta_{\text{straight}} = \frac{L_{\text{stance}}}{L_{\text{stance}} + V_{\text{straight}} t_{\text{swing}}}. \tag{2.7}$$

To use the constant k_β derived from sprint performance under 'straight' conditions to derive performance around a bend, we introduce the term v', the speed adopted in response to changes in duty factor because of changes in acceleration requirement. From equation (2.6):

$$\beta_{\text{bend}} = \frac{L_{\text{stance}}}{L_{\text{stance}} + v' t_{\text{swing}}}. \tag{2.8}$$

Therefore, using equation (2.4):

$$v' = \frac{L_{\text{stance}}(1 - k_\beta a)}{t_{\text{swing}} k_\beta a}. \tag{2.9}$$

This provides a closed-form solution for v' because the new speed is dependent on centripetal accelerations (equation (2.1)), which are themselves dependent on speed. So, the calculation of speed on the bend requires an iteration of equation (2.9), each time using the latest value for v' in the calculation of a (equation (2.1)). Using V_{straight} in the initial calculation for a, the asymptote for v' is approached after a few iterations, providing model speed around the bend V_{bend}.

Finally, the results are presented as times for 200 m races $T_{200\ \text{m}}$, taking into account the distance spent at V_{straight} along the straight S_{straight}, and at the reduced speed around the bends of combined distance S_{bend}:

$$T_{200\ \text{m}} = \frac{S_{\text{straight}}}{V_{\text{straight}}} + \frac{S_{\text{bend}}}{V_{\text{bend}}}. \tag{2.10}$$

For the first time, this model allows a simple prediction of indoor race speeds and times from only maximum 'straight' speed, t_{stance} and L_{stance}.

(b) *Model inputs*

Appropriate ranges of V_{straight} are derived from the 2004 Olympics for men ($N=105$) and women ($N=97$). Histograms (figure 2) show the distribution of 200 m published times for heats, quarters, semis and finals. In these races, the athletes sprinted around unbanked bends of such large radii that bias by lane assignment appears to be more closely related to psychological factors than mechanics. While an athlete sprinting at 10 m s^{-1} around a typical indoor bend of $r=20$ m experiences an increase in a of 12% above gravity (from equation (2.1)), sprinting around a typical outdoor bend of $r=40$ m results in only a 3% increase. We, therefore, take the outdoor races to be 'straight', while acknowledging this as an approximation.

The kinematic parameters are derived from observations reported by Weyand *et al.* (2000), in which the relevant values are shown to be remarkably consistent and independent of sprint performance, at least within each gender. We, therefore, use $t_{\text{swing}}=0.315$ s for male and female, and $L_{\text{stance}}=0.99$ m (male) or 0.90 m (female). Model results are insensitive to small variations in these parameters.

In order to calculate the influence of bends on total time for 200 m races, we use track dimensions for the venue of the 2004 World Indoor Championships (Budapest, Hungary): bend radii for lanes 1–6 are 17.5–22.5 m with 1 m intervals. The stagger largely occurs around the bend, so lane assignment has no bearing on the proportion of the race spent on bend and on straight: $S_{\text{bend}}=109.96$ m; $S_{\text{straight}}=90.04$ m.

Model relationships of indoor 200 m time by lane assignment and 'straight' 200 m times are shown underlying actual indoor results for the 2004 IAAF World Indoor Championships for all rounds for men ($N=45$) and women ($N=29$). Note that, in indoor competition, lane assignments are random at each stage

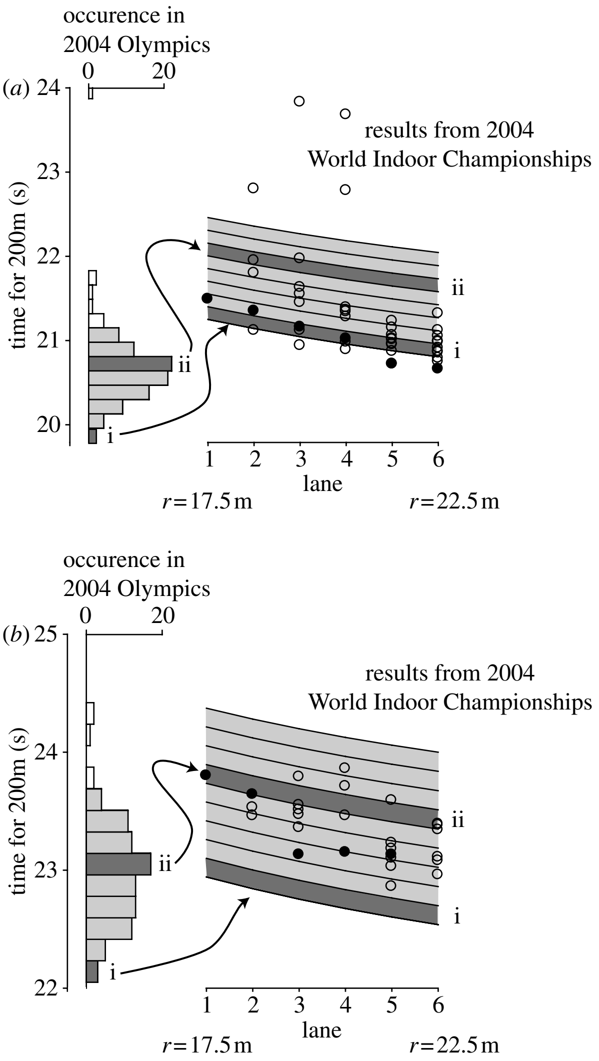

Figure 2. Two-hundred metre results for 2004 Olympics (outdoor) and 2004 World Indoor Championships, with model indoor results derived from outdoor ('straight') times for men (*a*) and women (*b*). Olympic results are presented as histograms on the left of each panel. Fastest (i) and mode (ii) Olympic and model times are highlighted in dark grey. Circles indicate results from all rounds of the World Indoor Championships; filled circles relate to results from each final. Model indoor results (curves) vary by lane and input 'straight' speed: competitors assigned lane 1 are at the greatest disadvantage as they have to run around tightest bends ($r=17.5$ m) and subsequently experience highest centripetal accelerations, requiring largest changes in duty factor in order to preserve limb forces during stance. Other than gravity, bend radius and the range of 'straight' velocities from the Olympic times, the only inputs to this constant force model are the leg protraction time t_{swing} (taken as 0.315 s for men and women) and distances covered during stance L_{stance} (taken as 0.99 m for men and 0.90 m for women) (Weyand *et al.* 2000). Sources of data: IAAF website, http://www.iaaf.org/wic04/. Olympics 2004 website, http://www.athens2004.com/.

(though outer lanes are filled preferentially if there are fewer than six competitors).

(c) *Approximations and simplifications*

The application of the above model is reliant on a number of additional assumptions that should be acknowledged. No account is taken of the variations in height associated with lane position (due to banking, competitors in outer lanes had to ascend for the bends and descend for the straights). However, if this were an issue, one would expect it to provide a disadvantage to outside lanes, which have greater variations in height. Strategic variations in speed through the race are also omitted (the model assumes the athletes are running at maximal speed at all times). Also, the model assumes indoor and outdoor athletes are similar, and always competing to their maximum potential. Therefore, combined with the inherent variation in athletic performances, perfect matches between model and measured indoor 200 m sprint times should not be expected. Indeed, the variability of the empirical data, and our desire to provide a model from first principles with as few simplifying assumptions as possible, precludes the addition of further factors to fine-tune the model to fit the race results. Whether our model should be viewed as satisfactory and informative depends on the requirements of the reader.

3. RESULTS AND DISCUSSION

Figure 2 shows the population histograms for 200 m times from the 2004 Olympics (left, taken to represent 'straight' sprint speeds), the resulting model curves, and the data from the 2004 World Indoor Championships grouped by lane assignment. The majority of the indoor results fall within the boundaries indicated with dark grey, which highlight best (i) and mode (ii) times. While scatter in the published indoor times is evident and unsurprising, and best and mode populations are not precisely predicted, the very simple 'constant limb force' model appears effective in accounting for the observed indoor performance according to lane. Times for the indoor finals (filled circles), the only races in which lane 1 is used, and in which the best performances would be expected, are remarkably well predicted for men and somewhat under predicted for the women. Two aspects are apparent from the model, broadly supported by the indoor race results:

(i) indoor times are higher than outdoor ('straight') times, and the approximate magnitude of the offset (around 1 s slower for indoor races) is predicted for men and women; and
(ii) the relationship with lane number, indicating a bias against inside lanes, is of an appropriate form, especially among athletes likely to be of most similar ability (the finalists). According to the model, this is because tighter bend radii result in greater increases in duty factor to preserve limb force, therefore requiring greater reductions in speed (and so worse race times).

Therefore, despite the simplifications involved in the application of the model, the very simple constant force assumption, combined with only two constrained kinematic parameters (both of which are well justified in the literature), seems effective and informative: even elite athletes appear constrained by limb force. We, therefore, conclude that our model results support the decision by the IAAF to abandon indoor 200 m races, as the bias against competitors assigned inside lanes is consistent with a physiological/mechanical explanation.

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