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A comparative analysis of pace, work and gait during national championship cross-country and road running events

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ABSTRACT
This study compared differences in running gait, intensity and performance across three national championship races comprised of different surface-conditions. Seven competitive under-20 male middle-distance athletes raced in all three events with no preparatory interference from researchers. The events comprised an asphalt road (Road) and dry, hard-pack (XC-dry) and wet, muddy (XC-wet) cross-country courses. Athletes wore GPS sports watches and inertial sensor (3 axis gyroscopes and accelerometers) foot pods to collect speed, total power output, form power output, propulsive power output, stride rate, ground-contact time, vertical oscillation, and leg spring stiffness data. The Road was quicker with greater total and propulsive power outputs (all $p < 0.01$), yet heart rate was not significantly different. There was no difference in form power or stride rate between Road, XC-dry and XC-wet. Road also demonstrated shorter ground-contact times and greater rate of force production during stance phase, greater leg spring stiffness (all $p < 0.05$) and greater ($p < 0.01$) and more variable stride length. Collectively, these findings indicate greater running economy during Road compared to XC-dry and XC-wet. Future research using spatiotemporal technology may consider how differences in running gait metrics over different surfaces and terrain profile influence training response(s).

1. Introduction

Across an annual season middle-distance runners compete and train on a variety of surfaces including synthetic athletic tracks, cross-country (off-road) and road (asphalt) where races and thus training differ in distance, duration, terrain, physiological requirements, and potentially spatio-temporal indices of running gait. While unsubstantiated it is believed within thew athletics community that the chronological order of cross-country and road season is appropriate for optimal development (Tulloh, 1998).

New technological developments enable athletes to wear spatio-temporal equipment that enables measurement of speed, distance, physiological effort (heart rate) and metrics of gait during training and races with no interference to performance or comfort (Hollis, Koldenhoven, Resch, & Hertel, 2019). Specific metrics of gait measured using such devices include: time spent in contact with the ground (ground contact time) where force is applied (Hayes & Caplan, 2012; Santos-Concejero et al., 2013); movement of the centre of mass (vertical oscillation) between steps (Moore, Jones, & Dixon, 2014); leg spring stiffness (peak force divided by the displacement during a step) (Butler, Crowell III, & Davis, 2003); stride rate and length (Mercer, Vance, Hreljac, & Hamill, 2002), and work rate indicated by power output which is calculated by estimating vertical, horizontal and lateral forces (Imbach, Candau, Chailan, & Perrey, 2020).

Laboratory work (Ferris, Liang, & Farley, 1999) has shown that runners pre-empting and then encountering different surface tensile properties adjust leg stiffness to maintain running form. In the field, the cross-country surface is more uneven and more compliant than either road or track surfaces. As such, off-road running at the same pace and when wearing the same footwear is associated with lower impact forces (Hollis et al., 2019; Tessutti, Trombini-Souza, Ribeiro, Nunes, & Sacco, 2010), increased leg stiffness (Ferris et al., 1999), increased ground contact time, greater muscle activation and thus mechanical work (Voloshina & Ferris, 2015) and metabolic expenditure (Jensen, Johansen, & Karkkainen, 1999).

The combination of greater muscle activation and work to maintain stability suggests cross-country facilitates strength or strength-endurance development in a specific manner, and which

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could benefit subsequent running disciplines within the annual season (Tulloh, 1998). Similarly, functional strength training (Beattie, Carson, Lyons, Rossiter, & Kenny, 2017) and explosive sport-specific activity (Beattie et al., 2017; Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999) has been linked to greater running efficiency and a greater ability to generate more horizontal force or impulse at take-off (Weyand, Sternlight, Bellizzi, & Wright, 2000). Such concurrent outcomes could be achieved with cross-country training with the more compliant surface associated with increased leg spring stiffness (Ferris et al., 1999) and ground contact time (Hollis et al., 2019) necessitating greater force production for the same running speed. This could be confirmed through comparisons of pace and spatio-temporal gait patterns associated with racing over cross-country and road.

Understanding differences between surfaces in competitive environments is limited where athletes wear spiked minimalistic shoes for cross-country racing compared with cushioned racing flats on the road. Differences in shoes may offset interactions in surface tensile properties, countering development, and the reduced overuse injury risk, while maintaining acute trauma risk associated with the non-uniformity of cross-country surfaces (Tessutti et al., 2010).

Consequently, the aim of this study was to compare differences in performance, intensity, and measures of running gait across three national championship races comprised of different surface-conditions.

It is hypothesised that while there will be no difference between measures of physiological intensity, surface-terrain will impair pace and metrics of gait related to faster running performances despite footwear differences.

2. Methods

2.1 Participants

Seven nationally competitive male U20 middle distance runners (mean ± SD: height 1.74 ± 0.07 m, body weight 55.8 ± 5.2 kg, 1,500m Pb for the 2017 track season 3:58 ± 0.18 min:sec, with an estimated $\dot{V}O_{2max}$ based on race times (Daniels, 2014) 67.6 ± 4.3) were recruited from the local running community for this study. Prior to inclusion, all participants were required to be free of injury, complete all 3 races, and provide written consent in accordance with the University Human Ethics Committee.

2.2 Testing

Participants were required to compete on three occasions in their standard distance for respective age category, each separated by one month. All events were mass start multi-lap. Race 1 (XC-dry) surface was hard pumice soil with short grass, 70 m elevation gain and 70 m descent over 5.1 km course and 2 different laps (Figure 1A). Race 2 (XC-Wet) surface was very wet and muddy, 118m elevation gain and 118 m descent over 3 laps totalling 6.15 km (Figure 1B). Race 3 (Road) surface was tar-sealed road, with 47m elevation gain and 47 m descent over 3 laps totalling 6.03 km, (Figure 1C).

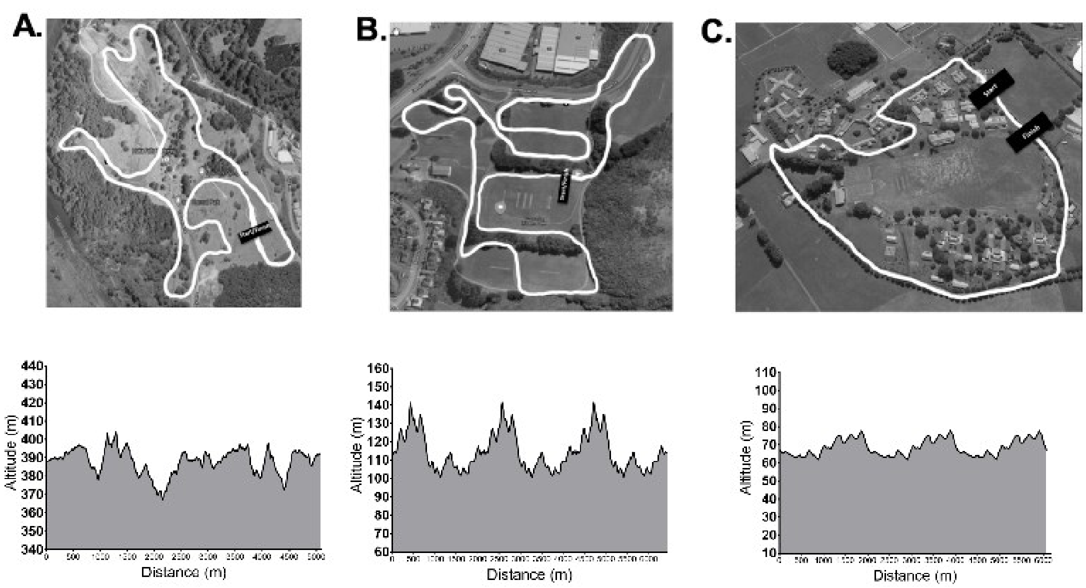

Figure 1: Course maps and elevation profiles for: A. North Island cross-country (XC-Dry); B. National cross-country (XC-Wet); and C. National road-running (Road) championship races.

There was no interference from the researchers in the athlete's preparation for this event where all participants wore cross-country spikes for the XC-Dry and XC-Wet, and traditional racing flats for the road race. Accommodation, sleep, dietary and warm-up strategies were freely selected to suit individual's preferences. The only requirement was to wear a Stryd Foot Pod (Stryd^{TM}, Colorado, USA) and Garmin 235 GPS watch at all events. The Stryd foot pod has shown inter-device validity (r = 0.8-0.9) and reliability (CV <3.5%) for metrics associated with gait including ground contact time (ms), vertical oscillation (mm), stride rate (spm), and stride length (m) (García-Pinillos et al., 2019) along with calculations for leg spring ($KN \cdot m^{-1} \cdot Kg^{-1}$), form power output (W), propulsive power output (W) and total power output (W) at a frequency of 1Hz. Additional data (speed ($m \cdot s^{-1}$) and heart rate (bpm)) was logged on the GPS sports watch, shown to have accuracy within 1% for distance during running activity (Johansson, Adolph, Swart, & Lambert, 2020) and r = 0.9 for photoplethysmography technology (Støve, Haucke, Nymann, Sigurdsson, & Larsen, 2019) were transferred to Stryd Power Centre web application, converted to CSV files and used for subsequent analysis.

2.3 Statistical Analysis

Descriptive variables are reported as mean ± SD. Within-individual coefficient of variation (CV%) determined variability for pace, heart rate and metrics associated with gait, across each race. An ordinary one-way analysis of variance (ANOVA) with Tukey's post-hoc multiple comparison was used to find the difference between surface-terrain for each dependent variable, with significance set at $p < 0.05$. All statistical analysis was performed using GraphPad Prism (version 7.0).

3. Results

Overall, race speed was significantly different for the three races (XC-Dry = 4.8 ± 0.2; XC-Wet = 4.4 ± 0.1; Road = 5.0 ± 0.1 $m \cdot s^{-1}$; $F_{(1.507,6.027)} = 30.01$, $p = 0.001$, Figure 2A) with post differences between Road vs XC-Wet (difference = 0.59 $m \cdot s^{-1}$, $p = 0.0002$), and XC-Dry vs XC-Wet (difference = 0.43 $m \cdot s^{-1}$, $p = 0.010$). Differences in speed were not reflected via physiological response as no differences was found for heart rate (XC-Dry = 168 ± 14; XC-Wet = 172 ± 14; Road = 169 ± 19 bpm; $F_{(1.092,4.37)} = 0.69$, $p = 0.463$).

Total power output differed significantly ($F_{(1.57,7.86)} = 24.11$, $p = 0.002$, Figure 2B) with post-hoc comparison differences for XC-Dry vs Road (difference = 25.1 W, $p = 0.019$), Road vs XC-Wet (difference = 52.9 W, $p = 0.013$), and XC-Dry vs XC-Wet (difference = 27.8 W, $p = 0.024$). While no overall differences in run form power ($F_{(1.015,5.08)} = 7.09$, $p = 0.055$, Figure 2C) were found, the reduced total power output meant there was significant differences in propulsive power ($F_{(1.269,5.08)} = 27.81$, $p = 0.003$, Figure 2D). Post-hoc comparisons revealed differences between races for XC-Dry vs Road (difference = -20.8 W, $p = 0.014$), Road vs XC-Wet (difference = 53.1 W, $p = 0.013$), and XC-Dry vs XC-Wet (difference = 32.3 W, $p = 0.014$).

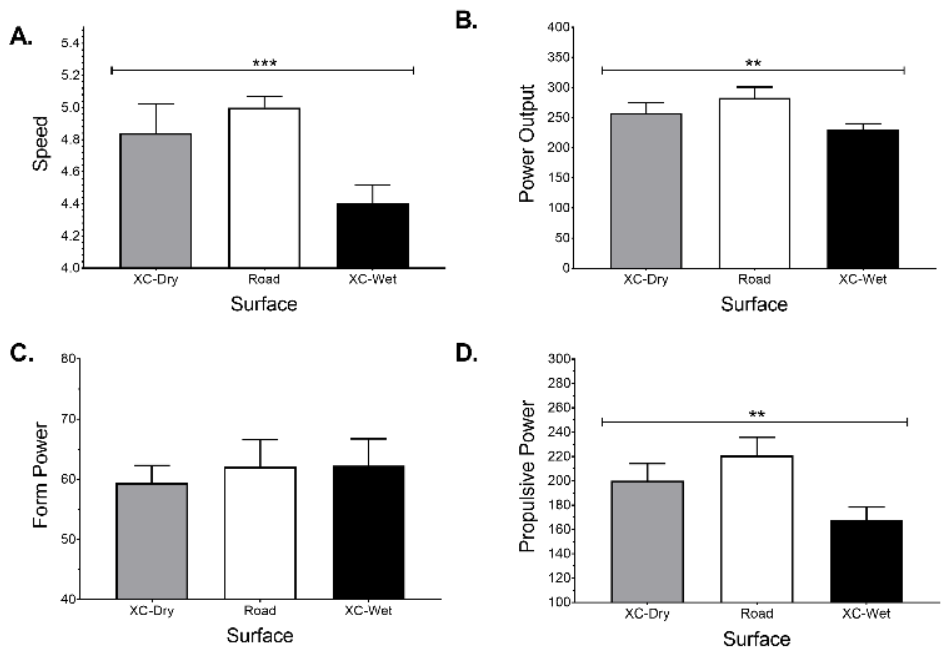

Figure 2: Mean ± SD comparisons of A. Speed ($m \cdot s^{-1}$), B. Total Power Output (W), C. Form Power (W), and D. Propulsive Power (W) during the three different races. *Where, XC-Dry is the NZ North island cross-country championships, Rd is the NZ National Road Running championships, and XC-Wet is the NZ National Cross-Country Championships.* (*** indicates overall significance $p < 0.001$, and ** indicated overall significance $p < 0.01$)

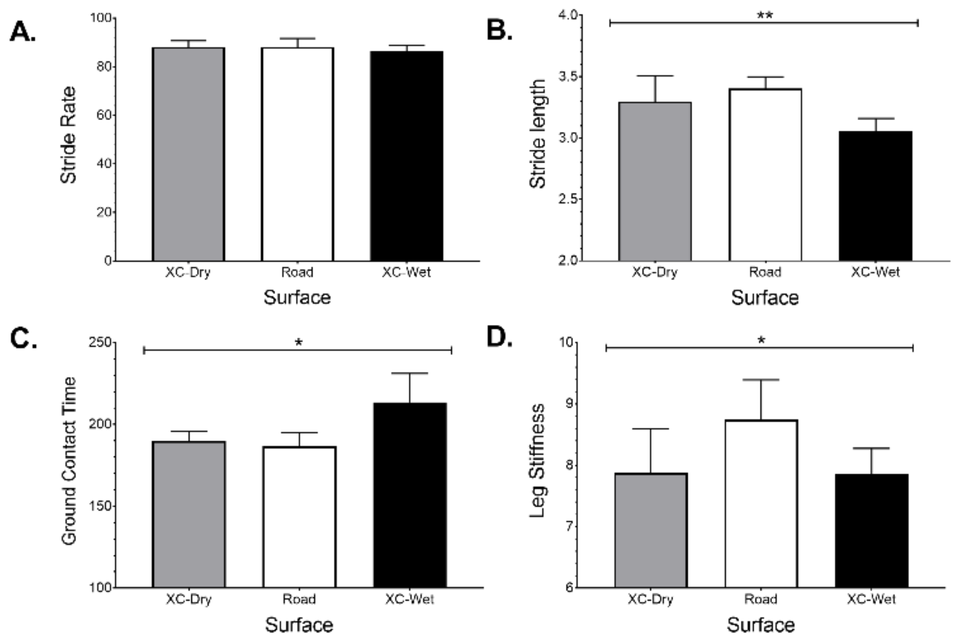

Figure 3: Mean ± SD comparisons of A. Cadence (rpm), B. Stride length (m), C. Ground contact time (ms), and D. Leg Spring ($KN \cdot m^{-1}$) during the three different races. *Where, XC-Dry is the NZ North island cross-country championships, Road is the NZ National Road Running championships, and XC-Wet is the NZ National Cross-Country Championships.* (** indicates overall significance $p < 0.01$, and * indicated overall significance $p < 0.05$)

Mean ± SD intra-athlete coefficient-variation in speed was 11.9 ± 2.6, 11.4 ± 1.2, and 8.0 ± 1.6 % for XC-Dry, XC-Wet and Road races, respectively. Similar variations in power output were seen including coefficient-variation of 12.1 ± 2.3, 18.1 ± 1.1, and 9.2 ± 1.8 % while heart rate (7.2 ± 4.9, 7.6 ± 4.6 and 5.3 ± 2.0 %) and form power (5.3 ± 2.1, 7.9 ± 5.6 and 4.9 ± 3.5 %) varied less for XC-Dry, XC-Wet and Road races, respectively.

Data analysis for metrics of gait (Figure 3 A-D), showed no overall difference for stride rate ($F_{(1.22,4.88)} = 5.24$, $p = 0.069$, Figure 3A), although post-hoc multiple comparison revealed significant difference ($p = 0.008$) between XC-Dry (88 ± 3 spm) and XC-Wet (86 ± 2 spm). Stride length differed significantly between the three races ($F_{(1.566,6.263)} = 20.52$, $p = 0.002$, Figure 3B) with post-hoc differences between XC-Dry-XC-Wet (difference = 0.24m, $p = 0.026$) and Road-XC-Wet (difference = 0.35m, $p = 0.002$). Overall difference were observed for ground contact time ($F_{(1.20,4.80)} = 9.16$, $p = 0.029$, Figure 3C) and leg spring ($F_{(1.49,5.94)} = 5.94$, $p = 0.045$, Figure 3D), but no post-hoc differences between races. There was no overall statistical difference for vertical oscillation ($F_{(1.04,4.18)} = 2.10$, $p = 0.219$).

Mean ± SD intra-athlete coefficient-variation for metrics of gait including stride rate were 3.9 ± 0.8, 4.8 ± 2.2, and 2.8 ± 0.6 %; stride length 9.5 ± 1.8, 6.1 ± 1.6, and 12.7 ± 3.2 %; ground-contact time 11.2 ± 3.1, 9.6 ± 1.4, and 9.9 ± 3.6 %; vertical oscillation 8.8 ± 2.0, 8.6 ± 2.4, and 7.1 ± 4.6 %; leg spring 7.4 ± 2.2, 10.0 ± 6.0, and 8.2 ± 5.8 %, for XC-Dry, XC-Wet and Road races, respectively.

4. Discussion

The aim of this study was to compare differences in performance, intensity, and measures of running gait across three national championship races comprised of different surface-conditions. The main findings were that dry and wet cross-country compared to road, and dry vs wet cross-country races, were ran at a slower pace with lower propulsive power output for the same physiological intensity. This decrease in pace was as associated with decreased stride length, increased ground contact time, and decreased leg spring stiffness.

Competition analysis of any sport is vital to understand determinants of inter- and intra- individual performance plus developmental perspectives within a competitive domain. The advent of spatiotemporal inertial sensors facilitates greater understanding of technical elements associated with running efficiency, performance, and health for surface-shoe interactions.

As the races chosen for this study were national championship races it was believed that all participants would perform to the best of their abilities despite the differences in terrain profile, surface conditions and racing dynamics. Whether this occurred is difficult to say, but similar average heart rate values suggest physiological intensity was equal. However, course profile and surface conditions combined with local climate meant that overall speed (Figure 2A) and total power output (Figure 2B) differed between races. Importantly, participants were able to maintain running form (Figure 2C), supported by no difference in vertical oscillation, regardless of course or conditions meaning the component of work related to forwards movement (propulsive power, Figure 2D) was greater for the road than XC-Dry, and XC-Wet, explaining the differences in speed per race. This also supports greater running economy for road running compared to XC-Dry and XC-Wet, and XC-Dry compared to XC-Wet which has previously been related to uneven surfaces (Voloshina & Ferris, 2015).

The increased running speed and thus greater propulsive work rate during the road race was connected to stride length, but not stride rate (Figure 3A-B). The more variable profile and the very muddy nature of XC-Wet had the shortest stride length, likely due to a need for stability and traction. While the road had the longest stride where the interaction between asphalt and racing flats provided ample traction and support. This reinforces previous work that shows stride rate remains constant at speeds between 3.2-4.1 $m \cdot s^{-1}$, whereas stride length increases (Cavanagh & Kram, 1989) and contributes towards approximately 87 % of changes in running speed (Delecluse, Ponnet, & Diels, 1998). The increase in stride length during the road race is likely due to greater rate of force production as supported by the decrease in ground contact time (Figure 3C). Causation being a more rapid stretch in muscles around the ankle and knee, eliciting more effective use of stored musculo-tendon elasticity during the concentric action of the stretch-shortening-cycle (Kyröläinen, Belli, & Komi, 2001). Whereas, it's difficult to ascertain effects of the more compliant surfaces to force production due to the shortening of stride length. Additionally, increased leg spring stiffness during the road race (Figure 3D) may not be expected in regards to surface stiffness properties (Ferris et al., 1999), but does point to a more economical running technique (Hardin, Van Den Bogert, & Hamill, 2004). The combined perception of shoe-surface interaction afforded by wearing racing flats as opposed to spikes for the two cross-country races likely explains this finding. Further research into the effects of surface-shoe interaction regarding greater speed capability, leg stiffness in relation to impact forces, subsequent greater musculoskeletal loading, and thus increased overuse injury risk needs to be performed with more participant in a controlled environment to determine this.

5. Limitations and Future Research

This work highlights the biomechanical, economical and performance differences between racing over different surfaces through use of inertial sensors but does have some limitations. Observing national championship races satisfies ecological validity within a competitive environment but we acknowledge the low sample size is a limitation. However, since this occurred it is more standard practise for athletes to own such devices and subsequent work with more statistical power could be performed. However, while differences in gait and factors relating to performance have been ascertained, the course profiles were all different, and athletes competing were free to undertake their own pre-race nutritional/supplementation strategies, warm-up routines, and race strategies. In addition, they competed on different profile courses with their own choice of footwear which may impact any understanding of surface effects on gait or economy. Future research needs to use similar technology to isolate running at controlled speeds with the same or different footwear to endorse the findings over different surfaces. This work should also consider the different profiles which may be useful to empower athletes/coaches to make more informed decisions regarding footwear and or technique.

6. Conclusion

The results of the present study show that competitive running over different surface compliance affects running economy due to changes in gait. Asphalt was faster and more economical than dry or wet cross-country races due to longer strides associated with shorter ground-contact times, and increased leg spring stiffness.

7. Practical implications for coaches and athletes include:

- Surface terrain does not interfere with physiological development.
- Athletes should use heart rates for monitoring intensity across surfaces whereas power output or pace should be surface specific.
- Running on asphalt increases rate of force production during ground contact which is beneficial to performance capability.
- Wearing spikes on grass could negate any health-related benefits associated with injury risk over cushioned shoes on asphalt.

Conflict of Interest

The authors declare no conflict of interests.

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