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MECHANICAL EFFICIENCY AND NEUROMUSCULAR REGULATION IN ELITE SPRINT ORIENTEERING: A HIGH-RESOLUTION COMPETITION CASE ANALYSIS

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ABSTRACT

Sprint orienteering requires rapid accelerations, repeated directional changes, and sustained high-intensity locomotion under cognitive load, yet mechanical efficiency and neuromuscular regulation during elite competition remain insufficiently explored. The aim of this study was to examine mechanical efficiency and neuromuscular regulation in elite sprint orienteering across different competition contexts. A high-resolution case-study design was applied, analyzing second-by-second wearable biomechanical data from two elite male orienteers across three sprint competitions each (national and European Championship events). Descriptive statistical analysis was performed, including mean ± standard deviation calculations, coefficient of variation, and Pearson correlation analysis. International races, particularly the Knock-Out Sprint format, were characterized by shorter ground contact times in both athletes (e.g., 225.7 ± 34.8 ms to 210.9 ± 21.3 ms in athlete 1), indicating enhanced reactive force application. Leg spring stiffness remained relatively stable across competitions (~8.3–8.4 in athlete 1 and ~9.3–9.5 in athlete 2), suggesting preserved elastic energy regulation despite reduced contact time. Substantial inter-individual differences were observed in mechanical variability (GCT CV ~10–15% vs. ~30–35%) and power–stiffness coupling ($r = 0.07–0.65$), reflecting divergent neuromuscular strategies under competitive stress. These findings indicate that sprint orienteering performance is influenced not only by physiological intensity but also by fatigue-related mechanical regulation. The small sample size and reliance on wearable-derived estimates limit generalizability. Practically, high-resolution biomechanical monitoring may support individualized performance profiling and training prescription. The originality of this study lies in its second-by-second competition analysis of mechanical efficiency in elite sprint orienteering.

Key words: orienteering performance, running biomechanics, stiffness regulation, stride variability, fatigue mechanics

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INTRODUCTION

Sprint orienteering is a high-intensity endurance discipline characterized by repeated accelerations, abrupt decelerations, rapid directional changes, and technical decision-making performed under time pressure. In elite orienteers, performance is also shaped by psychological and cognitive-related qualities that interact with physical and technical demands (Sirakov & Belomazheva-Dimitrova, 2021). While the physiological demands of orienteering have been well documented, including sustained high aerobic strain and significant anaerobic contribution (Smekal et al., 2003), considerably less attention has been directed toward the mechanical and neuromuscular determinants of sprint performance in this context.

Running performance is strongly influenced by biomechanical efficiency, particularly ground contact time (GCT) and leg spring stiffness (LSS). Shorter GCT has been associated with superior running economy and endurance performance, reflecting faster force application, improved elastic energy reutilization, and greater mechanical effectiveness in high-level running (Saunders et al., 2004; Moore, 2016). Reactive strength and stiffness regulation are also closely linked to sprint and high-speed running performance (Brughelli & Cronin, 2008).

The spring-mass model of running proposes that the lower limb behaves as a mechanical spring during ground contact (Blickhan, 1989). Within this framework, leg spring stiffness represents the ability to store and release elastic energy efficiently during stance. Leg spring stiffness can also be estimated in running using spring–mass modeling approaches derived from spatiotemporal and kinematic variables (Morin et al., 2005). Greater stiffness has been associated with improved running economy and endurance performance (Heise & Martin, 1998; Morin et al., 2007). Leg spring stiffness is therefore a useful indicator of how effectively elastic mechanisms contribute to running performance under different task demands (Morin et al., 2011).

Neuromuscular fatigue during running is often accompanied by increased ground contact time and altered stiffness regulation (Nicol et al., 1991; Morin et al., 2011). Such mechanical drift may compromise running economy and force transmission efficiency, particularly in events requiring repeated high-power accelerations. In sprint orienteering, where athletes frequently accelerate out of controls and negotiate sharp turns, the ability to maintain mechanical stability under fatigue may be critical for performance.

Recent advances in wearable inertial measurement systems, including foot-mounted devices such as Stryd, enable high-resolution biomechanical assessment in ecological competition environments. Validation studies have demonstrated acceptable reliability and concurrent validity of wearable-derived stride parameters, including contact time and vertical oscillation (García-Pinillos et al., 2021; Berzosa et al., 2024). In addition, running power metrics derived from wearable systems have been shown to provide meaningful insight into endurance performance and metabolic capacity in field settings (Karparova & Dimitrov, 2024).

Despite growing interest in running biomechanics and stiffness regulation, no study to date has examined second-by-second mechanical efficiency indicators such as ground contact time and leg spring stiffness during elite sprint orienteering competition across different competitive contexts. Understanding how these variables respond to fatigue and competitive level may provide insight into neuromuscular stability and mechanical performance determinants in this sport.

Therefore, the aim of this study was to examine mechanical efficiency and neuromuscular indicators in two elite male orienteers across national and European sprint competitions using high-resolution wearable data. Specifically, the study analyzed ground contact time, leg spring stiffness, mechanical variability, drift patterns, and power–stiffness coupling to characterize neuromuscular stability under fatigue and across competition formats.

METHODS

Study Design

This study employed a high-resolution case-study design examining second-by-second biomechanical responses during three sprint competitions per athlete (n = 2 elite male orienteers with more than 10 years of experience in the national teams – both junior and men). Data were collected during the Bulgarian National Sprint Orienteering Championships, the European Orienteering Championships Sprint Qualification, and the European Orienteering Championships Knock-Out Sprint Qualification. Only race segments (excluding warm-up and cool-down) were analyzed.

Biomechanical Data Acquisition

Biomechanical variables were obtained using the Stryd foot pod (Next Gen version, by Stryd Inc., USA), an inertial measurement device that provides running power and stride-related parameters derived from accelerometry and motion modeling.

Variables

The following biomechanical variables were analyzed:

- Mean ground contact time (GCT, ms)
- Ground contact time drift (%), defined as the percentage change between the first and second halves of each race
- Ground contact time variability (CV, %)
- Mean leg spring stiffness (LSS, device-derived units)
- Leg spring stiffness change (%), defined as the percentage change between race halves
- Leg spring stiffness variability (CV, %)
- Power–LSS coupling (r), representing the relationship between running power and leg spring stiffness across the race duration

All variables were derived from second-by-second wearable data collected during competition.

Statistical Analysis

All data were analyzed using a descriptive approach consistent with the exploratory case-study design (n = 2). Mean and standard deviation (SD) values were calculated for all biomechanical variables.

Ground contact time drift and leg spring stiffness change were calculated as the percentage difference between the first and second halves of each race. Mechanical variability was quantified using the coefficient of variation (CV, %).

The relationship between running power and leg spring stiffness was assessed using Pearson's correlation coefficient (r), calculated across the full race duration.

Given the small sample size, no inferential statistical tests were performed. The analysis focused on within-athlete comparisons across competition contexts and descriptive interpretation of fatigue-related mechanical patterns.

Ethical Considerations

All procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki. The study involved non-invasive analysis of performance data collected during official competitions, without any intervention or manipulation of the athletes' preparation or performance.

All participants were elite national-level orienteers and provided informed consent for the use of their wearable device data (Stryd) for research purposes. Participation was voluntary, and all data were anonymized prior to analysis.

Given the observational and non-invasive nature of the study, and the use of performance data obtained during regular competition settings, formal approval from an institutional ethics committee was not required according to local regulations.

RESULTS

Descriptive mechanical and neuromuscular variables obtained across the sprint competitions are summarized in Table 1. Both athletes demonstrated progressively shorter ground contact times during international competitions, with athlete 1 decreasing from 225.7 ± 34.8 ms (National) to 210.9 ± 21.3 ms (EOC KO), and athlete 2 from 221.0 ± 76.8 ms to 201.9 ± 61.3 ms. In contrast, mean leg spring stiffness remained relatively stable across conditions in both athletes (~8.3–8.4 in athlete 1 and ~9.3–9.5 in athlete 2). Marked inter-individual differences were observed in mechanical variability, with athlete 2 showing substantially higher GCT variability (CV ~30–35%) compared to athlete 1 (CV ~10–15%).

Table 1. Mechanical and neuromuscular variables across the sprint competitions.

Athlete	Competition	GCT (ms)	GCT Drift (%)	GCT CV (%)	LSS	LSS Change (%)	LSS CV (%)	Power –LSS r
Athlete 1	National	225.74 ± 34.78	5.05	15.38	8.35 ± 1.13	2.38	13.47	0.421
Athlete 1	EOC Sprint (Q)	216.33 ± 26.39	4.37	12.19	8.30 ± 0.89	-3.07	10.69	0.620
Athlete 1	EOC KO (Q)	210.86 ± 21.29	0.50	10.10	8.34 ± 1.02	4.41	12.19	0.072
Athlete 2	National	221.01 ± 76.82	-1.65	34.78	9.41 ± 2.07	8.02	21.99	0.451
Athlete 2	EOC Sprint (Q)	209.23 ± 64.47	-5.96	30.81	9.46 ± 1.35	2.85	14.30	0.553
Athlete 2	EOC KO (Q)	201.86 ± 61.29	-8.13	30.38	9.35 ± 1.90	9.00	20.37	0.654

Note. *GCT = ground contact time; LSS = leg spring stiffness as provided by the Stryd device. Values for GCT and LSS are presented as mean ± standard deviation. Drift and change values represent the percentage difference between the second and first halves of the race. CV (%) represents coefficient of variation. Power–LSS r represents Pearson's correlation coefficient calculated across the full race duration.*

Ground Contact Time (GCT)

Mean ground contact time was consistently shorter during international competitions compared to the national sprint for both athletes. Athlete 1 reduced mean GCT from 225.7 ± 34.8 ms (National) to 216.3 ± 26.4 ms (EOC Sprint) and 210.9 ± 21.3 ms (EOC KO). Similarly, athlete 2 demonstrated progressive reductions from 221.0 ± 76.8 ms (National) to 209.2 ± 64.5 ms (EOC Sprint) and 201.9 ± 61.3 ms (EOC KO). The shortest contact times in both athletes were observed in the KO Sprint format.

Figure 1 illustrates time-normalized ground contact time and leg spring stiffness profiles across the sprint competitions for both athletes. Both athletes demonstrated consistently shorter ground contact times during international competitions, particularly in the Knock-Out Sprint format. Leg spring stiffness remained relatively stable across all conditions, with minor fluctuations observed between race segments.

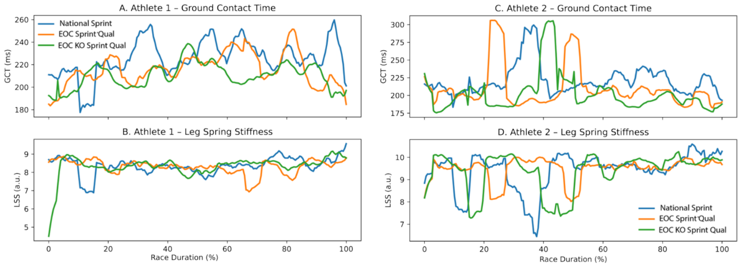

Figure 1. *Time-normalized ground contact time (GCT) and leg spring stiffness (LSS) profiles across sprint competitions in two elite male orienteers.*

Ground Contact Time Drift and Fatigue Response

Ground contact time drift patterns differed markedly between athletes. Athlete 1 demonstrated positive GCT drift during the National (+5.1%) and EOC Sprint (+4.4%) races, but only minimal drift in the KO format (+0.5%). In contrast, athlete 2 exhibited negative GCT drift across all competitions, with progressively larger reductions during EOC races (−6.0% to −8.1%), indicating shorter contact times in the second half of the race.

Leg Spring Stiffness (LSS)

Mean leg spring stiffness remained relatively stable across competitions for both athletes. Athlete 1 maintained values around 8.30 ± 0.89 to 8.35 ± 1.13 across all races, whereas athlete 2 demonstrated consistently higher stiffness values ranging from 9.35 ± 1.90 to 9.46 ± 1.35. Changes in LSS between race halves were relatively small in athlete 1 but more pronounced in athlete 2.

Mechanical Variability

Mechanical variability, expressed as coefficient of variation (CV%), differed substantially between athletes. Athlete 1 showed lower variability in both GCT (10–15%) and LSS (10–13%), particularly in international competitions. In contrast, athlete 2 exhibited considerably higher variability in GCT (30–35%) and LSS (14–22%), especially during the National event.

Power–LSS Coupling

Power–LSS coupling strength varied across competitions. Athlete 1 showed weak coupling in the KO format ($r = 0.07$), moderate coupling during the National event ($r = 0.42$), and strong coupling during EOC Sprint ($r = 0.62$).

Athlete 2 demonstrated consistently moderate-to-strong coupling, with the highest association observed in the KO Sprint ($r = 0.65$).

DISCUSSION

The aim of the present study was to examine mechanical efficiency and neuromuscular regulation in elite sprint orienteering across different competition contexts using high-resolution wearable data. The main findings indicate that international competitions, particularly the Knock-Out Sprint format, were associated with shorter ground contact times in both athletes, reflecting a more reactive contact profile. Despite these reductions, leg spring stiffness remained relatively stable across competitions, suggesting preserved elastic energy regulation. Additionally, distinct inter-individual patterns were observed in mechanical variability, fatigue-related drift, and power–stiffness coupling, indicating athlete-specific neuromuscular strategies under competitive stress.

1. *Mechanical efficiency under international race intensity*

Higher-level sprint competitions were characterized by a more reactive contact profile, as reflected by shorter ground contact times in both athletes. This finding is consistent with previous research linking reduced contact time to faster force application and improved running economy (Kyröläinen et al., 2001; Moore, 2016). The particularly short contact times observed in the Knock-Out Sprint format suggest that this competition type imposes greater reactive and neuromuscular demands compared to traditional sprint races.

As observed in the results, these reductions in contact time occurred without substantial changes in leg spring stiffness, indicating preserved elastic regulation under higher competitive demands. This combination suggests efficient force transmission and effective utilization of elastic energy rather than merely increased stride frequency. Notably, inter-individual differences were evident, with athlete 1 demonstrating more stable mechanical regulation and athlete 2 exhibiting greater variability and competition-dependent modulation.

Applied implication: International sprint formats may place greater demands on reactive strength qualities, particularly in shorter knockout events.

2. *Mechanical stability versus variability: Individual neuromuscular signatures*

A clear inter-individual difference emerged in mechanical variability. Athlete 1 demonstrated relatively low GCT and LSS variability, particularly in European competitions, suggesting stable stride mechanics under competitive stress. In contrast, athlete 2 exhibited substantially greater variability, especially in ground contact time.

Stride variability may reflect both neuromuscular control stability and the adaptive flexibility of the locomotor system under dynamic task demands (Nicol et al., 1991; Hamill et al., 1999).

Applied implication: Mechanical variability patterns may represent athlete-specific neuromuscular signatures, which could inform individualized strength and reactive training interventions.

3. *Neuromuscular fatigue regulation and GCT drift*

Ground contact time drift provides insight into fatigue-related mechanical alterations. Athlete 1 demonstrated minimal drift during the KO Sprint (+0.5%), indicating preserved mechanical stability under high-intensity conditions. In contrast, athlete 2 exhibited negative GCT drift (−6% to −8%) during European races, suggesting shortening of contact time in the second half, potentially reflecting increased stride reactivity or altered neuromuscular strategy under fatigue.

This pattern may reflect compensatory adjustments in stride timing or reactive behavior rather than unequivocal improvement in stiffness regulation. Previous fatigue studies have reported alterations in contact mechanics during prolonged or high-intensity efforts (Millet & Lepers, 2004).

Applied implication: Monitoring GCT drift during competition may help identify whether an athlete maintains reactive efficiency or compensates mechanically under fatigue.

4. Power–stiffness interaction and mechanical strategy

Power–LSS coupling revealed divergent strategies between athletes. Athlete 2 demonstrated strong coupling during the KO Sprint (r = 0.65), suggesting that increases in mechanical power were closely associated with increases in stiffness regulation. This may indicate reliance on elastic recoil mechanisms during high-intensity accelerations.

Athlete 1, however, demonstrated weak coupling in the KO format (r = 0.07), implying that stiffness regulation remained relatively independent of instantaneous power fluctuations. This may reflect a more stable mechanical template, with stiffness maintained across variable power outputs.

Applied implication: Athletes may rely on different neuromuscular strategies to generate power – some through greater stiffness modulation, others possibly through alternative stride adjustments such as cadence-related regulation.

5. Practical performance implications

From an applied perspective, the present findings suggest that sprint orienteers may benefit from training approaches targeting reactive strength, fatigue-resistant stiffness control, and stride stability under high-intensity conditions. Competition-specific biomechanical profiling may further support individualized programming.

From a methodological perspective, several considerations related to the use of wearable-derived biomechanical data should be acknowledged when interpreting the present findings.

Biomechanical variables in this study were derived from a wearable inertial measurement device (Stryd), which has demonstrated acceptable reliability and concurrent validity for spatiotemporal parameters such as ground contact time and vertical oscillation (García-Pinillos et al., 2021; Berzosa et al., 2024). However, it should be acknowledged that key variables, including ground contact time and leg spring stiffness, are model-derived estimates rather than direct mechanical measurements. While previous validation studies indicate stable repeatability across running speeds and field conditions, these estimates may not fully capture the complexity of movement patterns under the highly stochastic conditions of sprint orienteering, including sharp turns and rapid accelerations.

CONCLUSION

This high-resolution case analysis showed that elite sprint orienteering performance is characterized by distinct mechanical efficiency and neuromuscular regulation patterns that vary across competition levels and between athletes. International competitions, particularly the Knock-Out Sprint format, were associated with shorter ground contact times without marked reductions in leg spring stiffness, suggesting a more reactive mechanical profile with preserved elastic regulation. Inter-individual differences in variability, drift behavior, and power–stiffness coupling further indicate that wearable biomechanical monitoring can provide useful insight into athlete-specific neuromuscular strategies and support performance profiling and individualized training prescription.

Future research should examine larger samples and integrate contextual variables such as terrain and route complexity. The present findings highlight the value of wearable biomechanics for applied performance monitoring in sprint orienteering.

LIMITATIONS

Several methodological considerations should be acknowledged when interpreting the present findings.

First, the study included only two elite athletes, limiting generalizability. However, elite performance is inherently individual, and detailed case analyses may provide meaningful applied insight despite small sample sizes.

Second, stiffness values provided by the device are unit-specific and algorithm-dependent. While within-athlete comparisons remain valid, absolute stiffness values should be interpreted cautiously.

Third, race duration differed between competition formats, particularly in the KO Sprint event. Shorter duration may influence fatigue development and mechanical drift patterns, potentially contributing to observed differences in contact time and stiffness regulation.

Finally, spatial and contextual variables (terrain type, surface properties, route choice complexity, turning frequency) were not incorporated in the analysis. These factors may substantially influence ground contact mechanics and stride variability during sprint orienteering.

Despite these limitations, the present case analysis provides ecologically valid insight into competition-specific mechanical regulation in elite sprint orienteering.

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