



## Summary

**Background:** Pronounced lateral differences in musculoskeletal loading are widely considered a risk factor for the onset of various overuse injuries in the lower limbs in long-distance running. In a recent study, we described an innovative, easy-to-employ measurement setup based on commercially available inertial measurement units (IMUs) to assess tibial, sacral and scapular accelerations as well as possible asymmetries therein and to evaluate shock attenuation during running. We formerly employed the system under laboratory conditions as part of regular performance diagnostics for junior elite long-distance runners.

**Material and methods:** In this case report, we use that system to evaluate tibial and scapular loading of two athletes from the same cohort under field conditions during a high-altitude training camp. The athletes were chosen by their coach because of visually suspected pronounced asymmetries. We monitored the biomechanical loading of two athletes in four different high-altitude training sessions, ranging from low-intensity, flat gravel running to high-intensity interval training on an inclined asphalt road.

**Results:** Pronounced intra-individual differences in peak tibial and scapular accelerations were found for the two athletes, depending mainly on the slope of the running course and the running speed. In both cases, highest peak tibial accelerations were observed for downhill running ( $19 \pm 2$ ,  $g \approx 9.81 \text{ m s}^{-1}$ ). Visually suspected lateral asymmetries in tibial and scapular loading were objectively confirmed, reaching maximum values of 39% and 53%, respectively, depending on the particular session. While for Athlete 1, highest tibial asymmetries were observed for running on a flat track (39%), asymmetries for Athlete 2 were highest for running downhill (13%). Comparing the IMU data to laboratory-based isokinetic strength testing, it is suggested that lateral asymmetries in acceleration load in

## ORIGINAL PAPER

# Case report on lateral asymmetries in two junior elite long-distance runners during a high-altitude training camp

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## Introduction

Recently, we developed and described a measurement setup based on inexpensive, commercially available inertial measurement units (IMUs) to evaluate uniaxial and triaxial accelerations, shock attenuation and asymmetries at the tibiae, sacrum and scapulae during running [6]. First, we employed that system as an additional tool for performance diagnostics in junior elite long-distance runners under laboratory conditions [6]. Given the advantage of easy applicability also under field conditions, the aim of this case report was to assess lateral asymmetries in the tibial and scapular accelerations of two junior elite long-distance runners during a high-altitude training camp. The athletes' coach suspected "pronounced" chronic lateral asymmetries in their leg and shoulder running motor patterns on the basis of long-term subjective

observations. According to the coach's impression, the degree of asymmetries varied among different training session types (i.e. low-intensity sessions, demanding hilly runs or high-intensity interval sessions), but lacked objectification. In view of potentially harmful consequences that pronounced asymmetries may imply for the musculoskeletal system [8,3], we measured the tibial and scapular accelerations during different exercise types in the field.

## Methods

As in our previous study, we employed the same IMUs of a leading supplier (Xsens Technologies B. V., MTw Awinda, Enschede, Netherlands) and fixed them non-invasively at the anteromedial tibiae, the sacrum and the scapulae of the subjects in a well-defined, reproducible fashion. Details are described in [6].

running may be linked to asymmetries in muscular knee extension strength.

**Conclusions:** IMUs are a practical, reliable and easy-to-employ tool for evaluating musculoskeletal loading in running, especially under demanding training conditions in the field. In summary, the results of this case report suggest that the individual extent of asymmetries in tibial and scapular loading during running may be linked to exercise characteristics, intensity and probably also to an imbalance in isolated knee-extension capabilities. Level of Evidence: V.

#### Keywords

Ground surface– Inertial measurement unit (IMU)– Isokinetics– Scapula– Tibia

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### Kasuistik zu lateralen Asymmetrien bei zwei Nachwuchsleistungssport-Langstreckenläufern während eines Höhentrainingslagers

#### Zusammenfassung

**Hintergrund:** Ausgeprägte seitliche Asymmetrien in der muskuloskelettalen Beanspruchung der unteren Extremitäten werden gemeinhin als Risikofaktor für das Auftreten von Über- und Fehlbelastungen im Langstreckenlauf angesehen. In einer jüngst veröffentlichten Arbeit haben wir ein innovatives, einfach zu handhabendes Messsystem vorgestellt, mit dem auf Grundlage von handelsüblichen Inertialsensoren die an Schienbeinen, Kreuzbein und Schultern während des Laufens auftretenden Beschleunigungen erfasst werden können, einschließlich etwaiger Asymmetrien sowie zugehöriger Stoßdämpfung. Das Messsystem wurde dabei unter Laborbedingungen als Teil der regulären komplexen Leistungsdiagnostik im Nachwuchsleistungssport-Langstreckenlauf eingesetzt.

**Material und Methoden:** In den vorliegenden zwei Kasuistiken wurde das System unter Feldbedingungen zur Erfassung der tibialen und skapularen

#### Subjects

The participating two male junior elite long-distance runners were members of the German National Team and took part in Youth World and European Championships. At the time of measurement, the athletes were 18.4 and 16.8 years of age, while their masses, heights, body mass indexes and maximum oxygen uptake amounted to 65 kg, 184 cm, 19.2 kg m<sup>-2</sup>, 70.6 ml min<sup>-1</sup> kg<sup>-1</sup> and 68 kg, 180 cm, 21.0 kg m<sup>-2</sup>, 74.0 ml min<sup>-1</sup> kg<sup>-1</sup>, respectively.

#### Study design

The measurements were performed during the last week of a three-week high-altitude training camp (“sleep high, train high” at ≈2000 m above sea level) in the Tyrolian Alps (Austria). Among several training sessions of that week, four sessions were chosen for IMU acquisition, owing to their representative character for a broad variety of common exercise forms:

- S1. Low-intensity, flat gravel track running of 10 km at 11.4 km h<sup>-1</sup> (≈5: 16 min km<sup>-1</sup>)
- S2. Hilly mid-intensity (“demanding”) asphalt road and trail running of 8.7 km at 13.1 km h<sup>-1</sup> (≈4: 35 min km<sup>-1</sup>)
- S3. High-intensity interval training (HIIT) on tartan track consisting of 6 × 1000 m at 17.2 km h<sup>-1</sup> (≈3: 30 min km<sup>-1</sup>)
- S4. Uphill sprint running consisting of 10 × 200 m at 24.0 km h<sup>-1</sup> (≈2: 30 min km<sup>-1</sup>) on a uniformly ascending asphalt road with a grade of 11.4%.

The two athletes performed all sessions side-by-side and maintained the intended running speed by means of GPS-enabled sports watches (Garmin Forerunner 910XT or comparable), as

instructed by their professional coach. All four training sessions were completed with the same individual pairs of running shoes, thereby avoiding footwear-related intra-study effect [1,5]. A cyclist accompanied the two athletes with a mobile device for instant receiving and permanent storing of the IMU data. This accompanying is no longer required if the IMUs are operated as synchronised data loggers, as meanwhile provided by several manufacturers.

Approximately six months before and four months after the training camp, both athletes performed isolated, unilateral concentric isokinetic strength tests for their knee and hip joints (IsoMed 2000® with custom extensions, D & R Ferstl GmbH, Hemau, Germany) under laboratory conditions (Fig. 3(b)). In those tests, the athletes were asked to perform knee and hip extension tasks at constant angular velocities of 60° s<sup>-1</sup> and 180° s<sup>-1</sup>, each bout with five repetitions at maximum effort. The ranges of motion were set to a knee flexion angle of 15–110° (with 0° corresponding to an entirely extended knee) and to a hip flexion angle of –20° to +80° (with 0° corresponding to a vertical alignment of the thigh). The last three of five repetitions were analysed, yielding a lateral asymmetry index  $\Delta_{\tau}$  of mean joint torques for the left and right knee and hip, respectively. In analogy to Eq. (1) in Ref. [6], an asymmetry index for the knees and hips was defined as

$$\Delta_{\tau} \equiv \frac{\tau^{(L)} - \tau^{(R)}}{\frac{1}{2}(\tau^{(L)} + \tau^{(R)})}, \quad (1)$$

where  $\tau^{(L)}$  and  $\tau^{(R)}$  denote the mean torques during the isokinetic motion of the left and right knee or hip, respectively.

Beanspruchung von zwei Nachwuchsläufern derselben Kohorte im Rahmen eines Höhentrainingslagers genutzt. Die beiden Athleten waren dabei zuvor von ihrem Trainer aufgrund visuell vermuteter (deutlicher) Asymmetrien ausgewählt worden. Wir überwachten die biomechanische Beanspruchung der beiden Läufer bei vier verschiedenen Höhentrainingsseinheiten, die vom lockeren GA1-Dauerlauf auf flachen Wanderwegen bis hin zum hochintensiven Intervalltraining in Form von Bergan-Läufen auf Asphalt reichten.

**Ergebnisse:** Es wurden deutliche intra-individuelle Unterschiede in den tibialen und skapularen Spitzenbeschleunigungen beobachtet, die vor allem vom Gefälle der Laufstrecke und der Laufgeschwindigkeit abhingen. In beiden Fällen traten die höchsten tibialen Spitzenbeschleunigungen ( $19 \pm 2 g \approx 9.81 \text{ m s}^{-1}$ ) beim Bergab-Laufen auf. Die visuell vermuteten seitlichen Asymmetrien der Schienbein- und Schulterbeanspruchung konnten objektiv bestätigt werden und erreichten, abhängig von der jeweiligen Trainingseinheit, Spitzenwerte von bis zu 39% bzw. 53%. Während bei Läufer 1 die höchste tibiale Asymmetrie bei einem flachen GA2-Lauf vorlag (39%), trat die höchste Asymmetrie für Läufer 2 beim Bergab-Laufen im GA2-Tempo auf (13%). Ein Vergleich der Inertialsensordaten mit den Ergebnissen laborseitiger isokinetischer Krafttests legt nahe, dass ein Zusammenhang zwischen einer lateralen asymmetrischen Beschleunigungsbeanspruchung beim Laufen und einer Seitigkeit der Kraftvoraussetzungen der kniestreckenden Muskulatur bestehen könnte.

**Schlussfolgerungen:** Inertialsensoren stellen ein praktisches, zuverlässiges und nutzerfreundliches Werkzeug zur Erfassung der muskuloskelettalen Beanspruchung beim Laufen dar, insbesondere unter anspruchsvollen Trainingsbedingungen im Feld. Insgesamt lassen die vorliegenden Ergebnisse dieser Kasuistiken vermuten, dass die individuelle Ausprägung seitlicher Asymmetrien in der tibialen und skapularen Beanspruchung beim Laufen in Zusammenhang mit der Trainingsart und

## Results

Among all results, the demanding hilly asphalt road and trail running session S2 revealed several insights, making it worthwhile to start with that session (Fig. 1). The road grade, i.e. the running slope depicted in Fig. 1(a), altered tibial accelerations in both athletes throughout the course, cf. Fig. 1(b) and (c). In particular, significantly higher tibial accelerations ( $p < 0.001$ ) were observed during downhill running (e.g. between  $t = 2$  min to 5 min: total mean peak tibial acceleration for both athletes and legs of  $a = 19 \pm 2 g$ <sup>1</sup> and, conversely, significantly reduced tibial accelerations ( $p < 0.001$ ) were measured for uphill running (e.g. between  $t = 6$  min to 11 min:  $11 \pm 2 g$ ), as compared to flat segments (e.g. between  $t = 11$  min to 16 min:  $13 \pm 2 g$ ). The mean peak tibial accelerations of the total course amount to  $13 \pm 3 g$  for 3D acceleration and to  $9 \pm 2 g$  for its axial component (Fig. 1(e)).

Apart from these slope-induced differences in tibial accelerations, either of the two athletes exhibited lateral asymmetries in tibial acceleration, both in 3D vector magnitude and axial component (Fig. 1(e)). Athlete 1 showed increased accelerations on his left leg (red), while for Athlete 2 greater accelerations were observed for his right leg (blue). Those asymmetries become more pronounced and statistically significant ( $p < 0.001$ ) for all studied segments when considering the axial components (filled columns in Fig. 1(e)). The axial asymmetry index  $\Delta_{ax}$  of Athlete 1 ranges between +7% to +39%

(magenta labels on columns) depending on the slope, whereas, for Athlete 2 it takes negative values from -7% to -21%. Maximum asymmetry values were observed for Athlete 1 on the flat segments ( $\Delta_{ax} = +39\%$ ) and for Athlete 2 during downhill running ( $\Delta_{ax} = +21\%$ ).

The results of session S2 are confirmed and extended by the outcome of the training sessions S1 (easy flat run), S3 (1000 m HIIT on track) and S4 (200 m HIIT uphill) (Fig. 2(a)). To sum up, irrespective of the session, Athlete 1 exhibited an asymmetry of tibial acceleration towards his left leg, while Athlete 2 showed an opposite asymmetry towards his right leg, both of which are significant for the axial component ( $p < 0.01$ ). The corresponding axial asymmetry indexes amount to  $\Delta_{ax} = +3\%$  to +27% for Athlete 1 and to -5% to -12% for Athlete 2. Regarding mean peak scapular acceleration, contralateral asymmetries were observable as compared to the corresponding tibial accelerations: Athlete 1 exhibited a pronounced asymmetric load towards his right shoulder, reaching a maximum mean asymmetry index of  $\Delta_a = -53\%$  during downhill running (Fig. 2(b), shaded columns). Similarly, Athlete 2 showed a substantial asymmetry towards his left shoulder with a maximum asymmetry index of  $\Delta_a = +21\%$  during the downhill segments.

Finally, a comparison of the average asymmetry indexes of the four running sessions S1–S4 to the athletes' asymmetry indexes of their isokinetic concentric knee and hip extension tasks suggests a possible link (Fig. 3). For both athletes, the leg exhibiting higher tibial accelerations during running is apparently positively correlated with the stronger leg in isokinetic knee extension strength (Fig. 3(a)). For hip

<sup>1</sup> Note that the gravitational acceleration at 2000 m above sea level is still to good approximation the same as at zero altitude, the deviation being less than 1%.

-intensität sowie einer etwaigen muskulären Dysbalance zwischen linker und rechter Kniestreckerkette stehen könnte.

Evidenzklasse: V.

#### Schlüsselwörter

Isokinetik – Inertialsensor – Schienbein – Schulterblatt – Untergrund

extension strength, in contrast, no such clear lateral correlation is observed.

## Discussion

In view of our recent results on lateral asymmetries in junior elite long-distance runners [6], the outcomes of this case report are remarkable: Even though the two athletes belong to the same highly-trained, healthy cohort, their asymmetry indexes are in parts substantially beyond the empirical “normal” range of their peers. Their coach’s subjective visual impression of “pronounced” asymmetries is thus substantiated by objective quantitative IMU data. Second, those clear-cut, highly significant asymmetries in axial load become less pronounced or are even concealed when considering only the acceleration magnitude picture (cf. empty columns in Fig. 1(e)). Hence, triaxial measurements *and* analyses are confirmed to be essential for a valid assessment of asymmetry in tibial accelerations, as already suggested by our pioneer research and recent studies [2,4]. Finally, the two athletes showed deviations from their reference group in terms of a contralateral interrelation of tibial and scapular asymmetries and a reduced shock attenuation (e.g., for Athlete 1 45% remaining tibial acceleration shock at the scapulae vs. group mean of  $31 \pm 1\%$ , see green percentages in Fig. 2(b)).

With the data at hand, it can only be hypothesised if reduced shock attenuation might be a direct result of the observed knee-extending muscle asymmetries, or, for instance, is amplified by hip abductor instability and/or mediated by active counterbalancing effects in subsequent joints and muscles to compensate for a high tibial load

asymmetry. On the other hand, as discussed in [6], lateral asymmetries may represent a sensible and effective compensatory measure for individual anatomic and/or orthopaedic conditions, and in this sense reflect a favourable adaptation instead of an unfavourable maladaptation. Therefore, a thorough orthopaedic examination is generally recommended in the case of significant asymmetries [6]. For the present two athletes, however, those examinations did not yield any substantial anatomic and/or orthopaedic irregularities, suggesting that the observed asymmetries may actually be habitual. In essence, future research is needed to further elucidate the interplay of individual anatomic, orthopaedic and neuromuscular conditions on the one hand and motor control pattern asymmetries on the other hand, as it may represent a key factor to overuse injury prevention. Irrespective of the complexity of this problem, we encourage the implementation of suitable, running-specific strength tests for the hip abductors in the framework of standard performance diagnostics in elite running for providing a helpful additional objective criterion for (functional) hip stability.

Furthermore, this case report yields intriguing details on the interplay between ground surface, inclination and running speed, extending the results of our recent study [6]. For instance, the 1000 m intervals on tartan (S3) induced higher tibial accelerations than the demanding hilly run (S2) on asphalt, rocks and gravel because of the higher running speed and irrespective of the more elastic tartan surface (Fig. 2(a)). Interestingly, for the 200 m HIIT uphill repetitions, running speed is almost 40% higher than for the 1000 m intervals ( $17.2 \text{ km h}^{-1}$  vs.  $24.0 \text{ km h}^{-1}$ ),

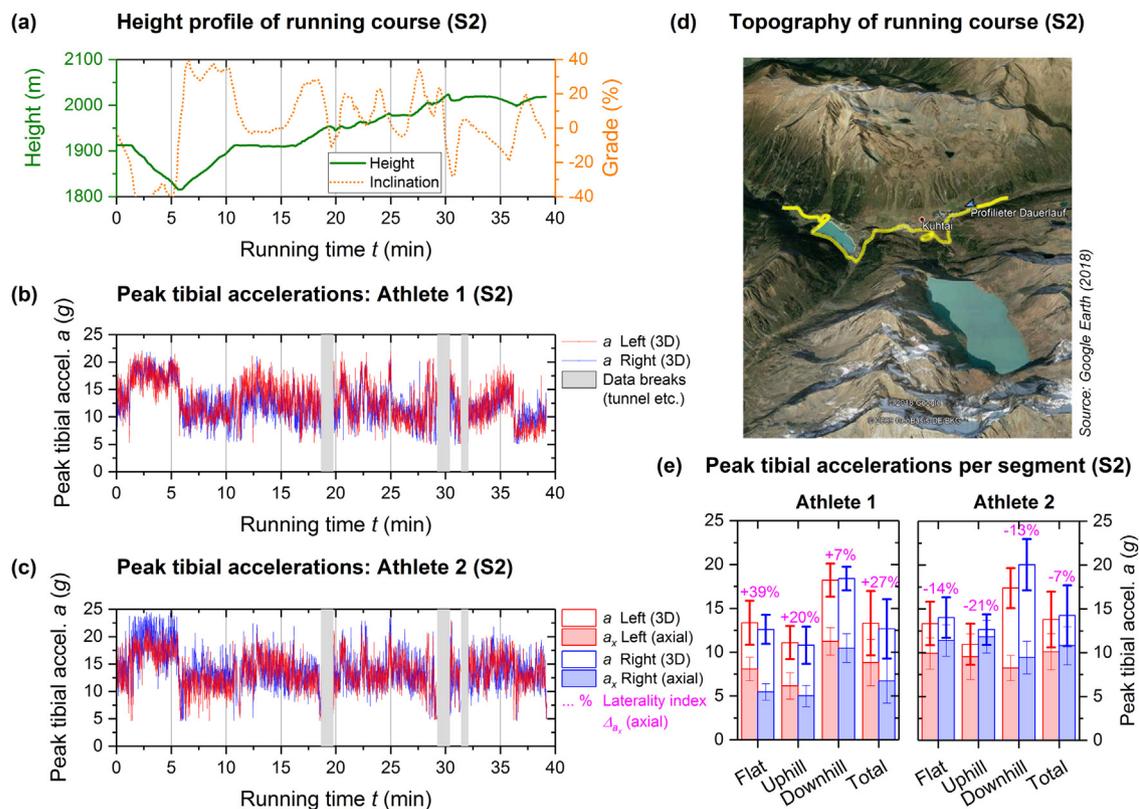


Figure 1

Results of training session S2 (Hilly, demanding run at 1815–2100 m above sea level, 250 m of total elevation). (a) Height profile and grade of course as function of running time. (d) Illustrative view of running course (based on satellite images provided by Google Earth®). (b and c) Peak tibial accelerations of Athletes 1 and 2 as a function of running time, and thus topography. Grey bars indicate short-term interruption of data acquisition due to challenging terrain features (tunnel, steep single-trail paths), rendering it complicated for the accompanying cyclist to stay close to the athletes. (e) Measured mean peak tibial accelerations (3D: empty columns; axial: filled columns) for left (red) and right (blue) leg as function of course inclination. Axial tibial asymmetry indexes  $\Delta_{ax}$  are indicated by magenta labels.

while the mean peak tibial acceleration load is not further increased, but actually slightly decreased ( $17 \pm 2 g$  vs.  $15 \pm 2 g$  for Athlete 1 and  $17 \pm 1 g$  vs.  $16 \pm 1 g$  for Athlete 2). This at first sight counterintuitive result is well explained by the biomechanics of uphill running, given the substantial +11% grade of the course: Running uphill, a fraction of the current (vertical) kinetic energy is converted into additional potential energy with each step, and thus is not dissipated during impact. The corresponding

lower vertical impact velocity results in a lower impact acceleration. For maintaining an efficient motor pattern despite that additional energetic demand, the runner intuitively reduces step length and increases step frequency, whereby tibial accelerations are further diminished. Finally, the finding of our recent study [6] that lateral tibial asymmetries are often independent of running speed are confirmed also by the two present athletes during sessions S1–S4, where the degree of asymmetry

rather depends on course inclination than on running speed (cf. magenta labels in Fig. 2(a)).

Comparing the peak accelerations of the two selected junior elite long-distance runners to their results for isokinetic knee extension tasks under laboratory conditions, the leg showing higher tibial accelerations during running was found to also be the stronger leg in terms of knee extension muscle strength (Fig. 3). Irrespective of being cause or effect, this result seems reasonable, considering the important to

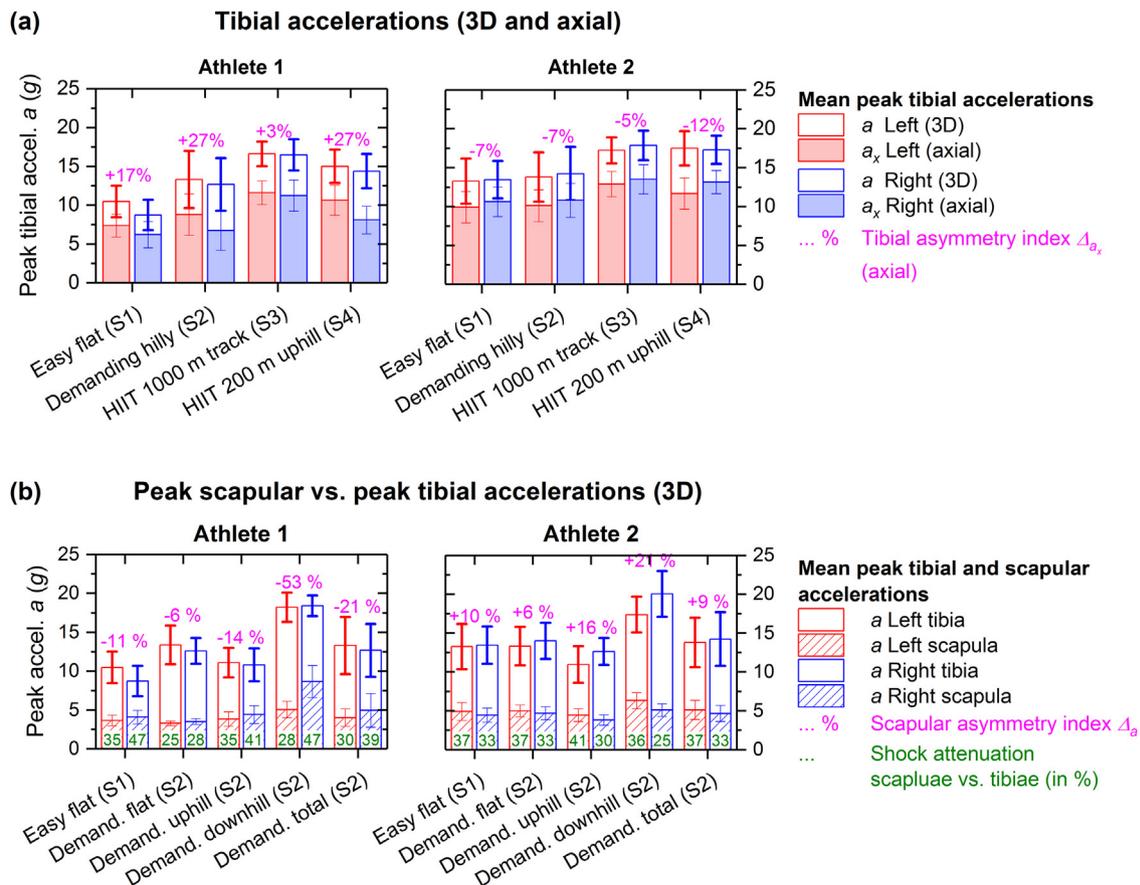


Figure 2

Asymmetries in tibial and scapular accelerations and shock attenuation during different training sessions. (a) Mean values  $\pm$  SD of peak tibial accelerations as a function of training session for left (red) and right (blue) leg in terms of magnitude (empty columns) and axial component (filled columns). Magenta labels indicate axial tibial asymmetry indexes  $\Delta_{a_x}$ . (b) Mean values  $\pm$  SD of peak tibial vs. unilateral peak scapular accelerations. Corresponding scapular asymmetry indexes  $\Delta_a$  are indicated by magenta labels while shock attenuation ratios are depicted as green percentages.

predominant role of the knee-extending muscles in both motor tasks: During stance phase in running, i.e. the period when peak tibial accelerations occur, the knee-extending muscles substantially contribute to counteracting gravity and mass inertia. For knee flexion angles beyond approximately  $30^\circ$ , only the quadriceps muscles fulfil that motor function, while the hamstring muscles can only flex the knee at such angles, according Lombard’s paradox [7]. Hip extension represents the second important motor contribution

during stance phase in running and to biomechanical running efficiency in general [7]. However, the hip extension strength asymmetries found in the two athletes did not match the asymmetries observed in their tibial accelerations. Given the complexity of the interplay of neuromuscular status and orthopaedic conditions, it is yet premature to conclude that hip extension might play only a subordinate role for tibial load. As only two athletes with pronounced asymmetries were studied, future research is needed to clarify these open questions. Nonetheless,

it is, to the best of our knowledge, the first time that laboratory-based isokinetic joint strength tests are discussed in the context of limb laterality of motor patterns in junior elite long-distance runners under field conditions.

### Conclusions for practitioners

- IMUs enable the practitioner to substantiate (or refute) subjective visual impressions of asymmetric

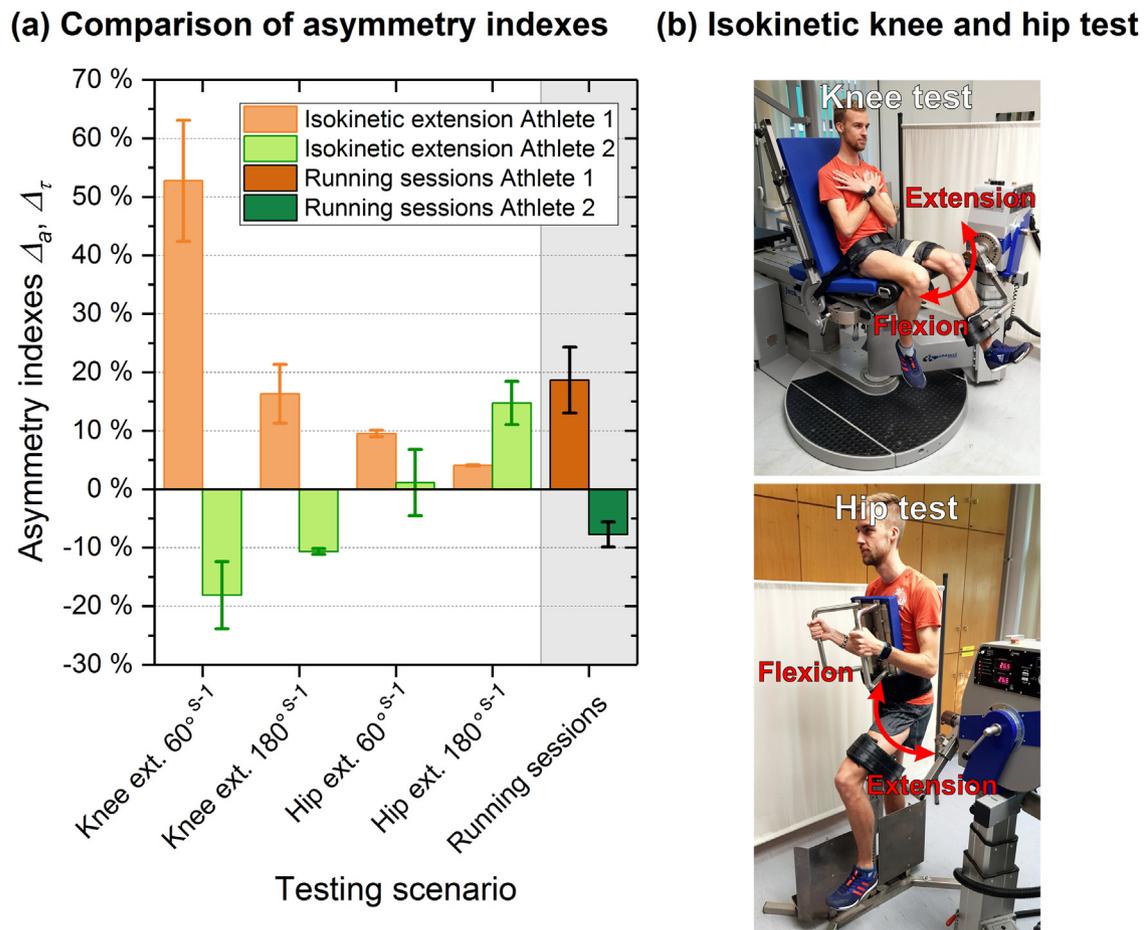


Figure 3

Comparison of asymmetries as detected by IMU sensors in complex running motion and muscular knee and hip extensor strength as measured in isolated isokinetic concentric tasks. (a) Comparison of asymmetry indexes. Error bars depict the standard error. (b) Schematic photos of isokinetic knee (top) and hip (bottom) extension tasks at 60° s<sup>-1</sup> and 180° s<sup>-1</sup>. (The depicted test person does not belong to the group of athletes discussed in the text.)

musculoskeletal loading during running under field conditions.

- Evidence is given that triaxial measurements are essential for a valid assessment of acceleration load in running. In contrast, important features of symmetry and shock attenuation may stay concealed in uniaxial-only measurements.
- Lateral asymmetries in muscular knee extension strength may be linked to pronounced lateral asymmetries in tibial load during running.

### Conflict of interest

There is no conflict of interest.

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