Mechanical, Metabolic and Perceptual Response during Sprint Training

Introduction

Sprint ability is a key factor in many sports. Thus, it is the focus of many training programs. Sprinting requires athletes to produce high speeds and cover given distances in the shortest possible time, or alternatively to cover the largest possible distances in a given period of time [22]. Phosphocreatine stores are vitally important in sprint performance, and are severely depleted after 5–7 s of sprinting [16]. During a longer distance sprint, such as a 100 m track and field event, anaerobic glycolysis provides the bulk of the adenosine triphosphate (ATP) needed to complete the sprint with minimal impairment of velocity (55–75 % of metabolic energy) [7, 14, 16]. An excessive number of repeated sprints during training sessions may lead to a significant reduction in ATP concentration, an accumulated loss of adenine nucleotides [3], and increased levels of superoxide radicals, which may eventually evoke muscle damage [26]. This large ATP depletion may produce a long recovery time requirement and impairment in muscle force production [12]. It has been suggested that muscle function impairment may be a result of H+ accumulation and an increase in inorganic phosphate [1]. Furthermore, there has been demonstration of a strong association between low intracellular pH and decreased force and power [8]. In addition, an increase in blood ammonia levels during short-term, high-intensity exercise is usually interpreted as indicative of accelerated ammonia production in muscles, resulting from the deamination of AMP to IMP. The purine nucleotide cycle serves, among other functions, to maintain a high ATP/ADP ratio [15] and acts as an emergency mechanism to prevent muscle ATP from falling to critical levels under conditions of high metabolic stress. In addition, the exponential increase in accumulation of H+ induces failure of excitation contraction coupling and impairment of sarclemmal excitability [24]. Therefore, knowledge of changes in blood lactate and ammonia concentrations during training sessions would provide valuable information about the physiological stress induced.

Blood lactate and ammonia measurements are expensive and invasive techniques, which means...
they are not feasible during regular training. However, relationships have been observed between these blood metabolites (lactate and ammonia) and jump height loss during resistance training [25], typical 400 m running sessions [11], and repeated sprint sessions with short recovery times (30 s) [20]. The strong correlations (0.92–0.97) observed between jump height loss and blood lactate and ammonia support the use of jump height for monitoring fatigue induced in training sessions [20, 25]. However, to our knowledge, the relationships between jump height and metabolites during a typical sprint session, including maximal sprinting with a theoretical full recovery period, have not yet been studied.

Previous studies that examined the mechanical and metabolic responses in sprinting used repeated sprints protocols with a fixed number of sprints and recovery periods shorter than 1 min [5, 19, 30]. Fixing the number of sprints may induce great variability between athletes in terms of the increment in running time, which is expressed as the fatigue index (FI) induced by the exercise [21]. This high variability in performance decrement among subjects may be associated with considerable changes in physiological responses and, consequently, different adaptations. Thus, determining a given level of fatigue to induce a more homogeneous response might be useful in protocols aimed at studying fatigue during sprint training sessions, since a standardized state of fatigue is induced.

In the absence of direct measurements, many coaches use the rating of perceived exertion (RPE) scale [6] in an attempt to gain information about the training load. So far, coaches have used the more traditional RPE scale to monitor the intensity of effort in endurance exercise [27], to estimate the level of effort or fatigue induced by resistance exercises [31] and during actual performance in specific sports [18]. However, although sprint training is used by almost every athlete, the perceptual, mechanical and metabolic responses induced by a typical sprint training session have not been described in detail. A better understanding of the individual mechanical and metabolic responses to typical sprint training and during the short-term post-running recovery period may help to improve the sprint training process and recovery strategies. Furthermore, individualizing the sprint dose from a variable that expresses performance impairment and its relationship with physiological responses may be relevant to individualized load prescription. Therefore, the aims of the present study were: 1) to analyze the acute perceptual (RPE), mechanical (speed and jump height loss) and metabolic (blood lactate and ammonia) responses to sprint training sessions, and 2) to determine whether perceptual or mechanical responses could be used to monitor neuromuscular fatigue during a sprint training session.

**Methods**

**Participants**

9 high-level male sprinters (age 23.1 ± 4.4 yr, body mass 73.7 ± 4.6 kg, height 177.6 ± 5.9 cm; body fat 9.6 ± 2.9 %) took part in the study. Their best performances over 100 m were in the range 10.29–11.17 s (7 of them had recorded performances below 11.00 s) and they had been competing for at least 5 seasons. Each athlete participated in national or international events during this period, and all of them were highly trained and familiarized with the testing exercises. One of them was the national record holder over 200 m (20.47 s) at the time of measurement. No physical limitations or musculoskeletal injuries that could affect testing were reported. The present investigation met the ethical standards of this journal [13] and was approved by the Research Ethics Committee of Pablo de Olavide University. After being informed of the purpose and experimental procedures, subjects signed a written informed consent form prior to participation.

**Experimental design**

Athletes performed bouts of 40 m sprints at the highest possible speed with a recovery period of 4 min between attempts until there was a 3 % decrease from the best time recorded for each athlete. We used a percentage-based FI score to individualize the prescription of sprinting load and attenuate the increased variability seen in fixed sprint protocols [21]. An FI target of 3 % was chosen since the athletes were specialists in short distances (maximum 200 m). Thus, a high FI was not advisable for improving their performance. Furthermore, a pilot study showed that this value was a common FI achieved during typical sprint training sessions using 40–80 m sprint distances. In addition, 10 s after each sprint, RPE was recorded and a countermovement jump (CMJ) was performed. Blood lactate and ammonia concentrations were measured 1 min after each bout. Testing sessions were always carried out after a full resting day, at the same time of day (18:00–20:00 h) and under similar environmental conditions (20–22 °C and 55–65 % humidity). A standardized warm-up protocol was used, consisting of: 1) 5 min of running at a self-selected easy pace; 2) 5 min of joint mobilization exercises; 3) two 30 m running accelerations; and 4) 5 CMJ with increasing intensity.

**Measures**

**40 m sprint time**

Sprint times were recorded for 40 m distances using photocell timing gates (Polifemo Radio Light, Microgate, Bolzano, Italy). The sprint test was conducted on a synthetic outdoor track (Mondo). A standing start with the lead-off foot placed 1 m behind the first timing gate was used. The bouts were separated by 4 min for recovery. The sprint was standardised as follows: Participants used a standard crouched position start with the toes of their preferred leg behind the start line. Once in position, participants were instructed to lean forward and hold their body mass over their forward leg, and they were then given a ‘3-2-1-go’ countdown. Athletes were prompted to accelerate maximally, and to attempt to cover the sprint distance as fast as possible. Test-retest reliability of 40 m sprint time was measured by coefficient of variation (CV) and intraclass correlation coefficient (ICC) with 95 % confidence intervals (95 %CI). This test showed very high reliability (CV: 0.6 %, ICC: 0.994 (0.975–0.999)).

**Countermovement jump height**

Jump height was calculated from flight time using an infrared platform (Optojump, Microgate, Italy). The infrared platform estimates the jump height from the flight time using the following equation: $h = \frac{t^2 \times 1.22625}{b}$, with $h$ being the jump height in meters and $t$ being the flight time of the jump in seconds. During the CMJ, the subject was instructed to rest his hands on his hips while performing a downward movement to reach about 90 ° of knee flexion, followed by a vertical jump of maximum effort. All subjects were instructed to keep their knees straight during the flight phase of the jump, and to land in an upright position in order to avoid the possibility of overestimation of jump height.
through the athlete ‘tucking’. For the pre-values, 3 maximal CMJs, separated by 30 s rests, were performed. The average value of the 3 jumps was used for the subsequent statistical analysis. 10 s after each sprint, a single CMJ was performed in an attempt to minimize the fatigue induced by the full CMJ test. The reliability for the CMJ test was CV: 2.7 %, and ICC: 0.978 (0.958–0.998).

Mechanical measurements of fatigue
2 different methods were used to quantify the extent of fatigue induced by the sprint session. The first method analyzed the percentage increment in time from the fastest sprint. Athletes performed 40 m sprints until an FI of 3 % was attained twice consecutively. The second method involved the calculation of the percentage change in CMJ height pre-post each sprint.

Ratings of perceived exertion (RPE)
Values were obtained using the 15-category Borg RPE scale [6]. Prior to testing, investigators verbally explained the details of the RPE scale. Perceived exertion was defined as the subjective intensity of effort that was felt after each sprint. 10 s after each sprint, verbal RPE values were provided by each athlete.

Blood lactate and ammonia analyses
Capillary blood samples for the determination of lactate and ammonia concentrations were obtained from the fingertip before exercise and 1 min after each bout. A portable lactate analyzer (Lactate Pro LT-1710, Arkray, Kyoto, Japan) was used for lactate measurements. Ammonia was measured using a portable ammonia analyzer (PocketChem BA PA-4130, Menarini Diagnostics, Florence, Italy). Both devices were calibrated before each exercise session according to the manufacturer’s specifications.

Statistical analyses
The values are reported as mean ± standard deviation (SD). Statistical significance was established at the P < 0.05 level. Test-retest absolute reliability was measured by CV, whereas relative reliability was assessed by ICC and 95 %CI calculated using the one-way random effects model. The within-subjects model accounted for the repeated measures of each variable. The homogeneity of variance assumption was not violated. Relationships with Pearson’s coefficients (r) and 95 %CI were used to calculate the respective relationships between performance parameters analyzed. The standard error of the estimate (SEE) was calculated. The magnitude of correlation was assessed with the following thresholds: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; and > 0.9–1.0, almost perfect [17]. The statistical analyses were performed using a statistical package (SPSS Inc., version 18, Chicago, IL).

**Results**

Descriptive characteristics of the protocol are reported in Table 1. The fastest 40 m sprint time was 5.04 ± 0.15 s (Table 1), and pre-values for CMJ height were 48.2 ± 5.5 cm. The number of sprints completed until a speed loss of 3 % was reached was 13 ± 3 sprints. After the last sprint, the CMJ height loss observed was 14.4 ± 4.5 % and RPE values were 17 ± 3. Blood lactate and ammonia concentrations after the last sprint were high (14.3 ± 3.4 mmol·l⁻¹ and 122 ± 33 µmol·l⁻¹, respectively) even with a large recovery time between bouts. However, all dependent variables analyzed showed high variability between athletes (sprints performed: 7–16 bouts; jump height loss: 9.0–22.6 %; lactate: 10.0–20.6 mmol·l⁻¹; ammonia: 79–172 µmol·l⁻¹; RPE: 10–20, Table 1).

Relationships between perceptual and mechanical measures of fatigue and metabolic responses
When all data were pooled, all relationships analyzed between perceptual and mechanical parameters and metabolic responses were significant (P < 0.05). Jump height loss showed almost perfect relationships with both blood lactate (r = 0.96 (0.95 to 0.97)) and ammonia (r = 0.95 (0.94 to 0.95)) concentrations (Fig. 1). The number of sprints performed and RPE values both showed very large relationships with blood lactate and ammonia concentrations (Fig. 1). Speed loss showed large relationships with both lactate and ammonia levels (r = 0.67 (0.58 to 0.75)). In addition, an almost perfect curvilinear relationship was observed through the athlete ‘tucking’.

### Table 1

<table>
<thead>
<tr>
<th>Athlete</th>
<th>T40 (s)</th>
<th>Sprints (n)</th>
<th>Speed Loss (%)</th>
<th>CMJ loss (%)</th>
<th>Lactate (mmol·l⁻¹)</th>
<th>Ammonia (µmol·l⁻¹)</th>
<th>RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.93</td>
<td>16</td>
<td>3.4</td>
<td>18.8</td>
<td>18.3</td>
<td>161</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>4.93</td>
<td>15</td>
<td>3.7</td>
<td>13.1</td>
<td>13.4</td>
<td>113</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>4.92</td>
<td>16</td>
<td>3.7</td>
<td>22.6</td>
<td>20.6</td>
<td>172</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>5.00</td>
<td>13</td>
<td>3.2</td>
<td>18.3</td>
<td>15.4</td>
<td>150</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>4.88</td>
<td>13</td>
<td>4.5</td>
<td>9.0</td>
<td>11.4</td>
<td>92</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>5.19</td>
<td>7</td>
<td>4.2</td>
<td>9.8</td>
<td>10.0</td>
<td>79</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>5.03</td>
<td>13</td>
<td>2.8</td>
<td>12.6</td>
<td>14.5</td>
<td>118</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>5.21</td>
<td>16</td>
<td>3.8</td>
<td>13.3</td>
<td>13.5</td>
<td>123</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>5.30</td>
<td>11</td>
<td>3.2</td>
<td>12.5</td>
<td>11.9</td>
<td>89</td>
<td>16</td>
</tr>
<tr>
<td>Mean</td>
<td>5.04</td>
<td>13</td>
<td>3.6</td>
<td>14.4</td>
<td>14.3</td>
<td>122</td>
<td>17</td>
</tr>
<tr>
<td>SD</td>
<td>0.15</td>
<td>3</td>
<td>0.5</td>
<td>4.5</td>
<td>3.4</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>Max</td>
<td>5.30</td>
<td>16</td>
<td>4.5</td>
<td>22.6</td>
<td>20.6</td>
<td>172</td>
<td>20</td>
</tr>
<tr>
<td>Min</td>
<td>4.88</td>
<td>7</td>
<td>2.8</td>
<td>9.0</td>
<td>10.0</td>
<td>79</td>
<td>10</td>
</tr>
</tbody>
</table>

T40: The fastest 40 m running sprint time
Sprints: Total number of sprints performed until achieving a fatigue index of 3 % in 2 consecutive sprints
Speed Loss: Maximal relative sprint time increment from the fastest sprint time experienced during the protocol
CMJ height loss: Maximal relative jump height decrement experienced during the protocol from the pre-values jump height
Lactate: Blood lactate concentration attained 1 min after the completion of the last 40 m sprint
Ammonia: Blood ammonia concentration attained 1 min after the completion of the last 40 m sprint
RPE: Ratings of perceived exertion obtained 10 s after the completion of the last 40 m sprint using the 15-category Borg scale
between blood lactate and ammonia concentrations \((R^2=0.96\text{ (0.95 to 0.97)}\), \(\odot\) Fig. 2).

**Discussion**

To the best of our knowledge, this is the first study to use perceptual, mechanical and metabolic responses to objectively monitor the fatigue induced by sprint training typically used by sprinters. Unlike previous studies that analyzed the fatigue induced by RSA protocols consisting of short-duration sprints (<10 s) interspersed with brief recoveries (<60 s) [10], the present study analyzed short sprints (40 m running sprints) with a recovery period of 4 min between bouts until there was a 3% decrease from the best time recorded for each athlete. The distance and recovery used in our study were chosen according to habitual workout routines for sprinters in order to have practical applicability. The high correlations observed between CMJ height loss and metabolic responses suggest that CMJ height might be used as a simple method of determining fatigue during sprint-training to individualize load prescription. Other variables such as the number of sprints performed, RPE or speed loss might also be used, although the estimation power appears to be lower. This information is relevant because it provides meaningful feedback to coaches about the metabolic response induced by specific sprint training protocols in relation to the resulting deterioration in acute jumping performance.

The findings obtained in the present study strongly support the use of CMJ height for monitoring and quantifying neuromuscular fatigue induced by the sprint training session. Jump height...
loss showed almost perfect relationships with both blood lactate \((r = 0.96)\) and ammonia \((r = 0.95)\) concentrations (Fig. 1). Furthermore, an almost perfect relationship was observed between blood lactate and ammonia concentrations \((R^2 = 0.96, \text{ Fig. 2})\). Previous studies have also observed a relationship between these metabolites and CMJ height loss during typical 400 m sessions or repeated sprint tests \([11, 20]\). To the best of our knowledge no data are currently available about when a sprint training session should be interrupted; in fact, the topic of the appropriate dose in sprint training sessions is controversial \([11, 21]\). While the present study does not produce a definitive answer to that question, it does, however, provide us with some valuable information that may indicate when it could be appropriate to end a sprint training session. Current knowledge of skeletal muscle fatigue suggests that during intense consecutive contractions, the onset of fatigue has a metabolic basis \([1]\). In addition, this metabolic stress may induce neural adjustments such as a reduction in the efficacy of signal transmission in the neuromuscular junction \([24]\) and alterations in neuromuscular activation of the contracting musculature \([4]\). Thus, the criteria for stopping a sprint session should be based on metabolic and mechanical stability instead of the previously widely-used fixed number of sprints. Therefore, the almost perfect relationships observed between blood lactate and ammonia concentrations and CMJ height loss may allow accurate assessment of neuromuscular fatigue induced during a typical sprint training session. A jump height loss of 8–10% corresponds approximately to 8–10 mmol·l\(^{-1}\) and 70–80 µmol·l\(^{-1}\) of blood lactate and ammonia, respectively, representing the onset of metabolic instability. Therefore, jump height may offer a cheap and easy way to measure individualized fatigue induced during typical sprint training without the need for expensive and invasive techniques, which are unfeasible during regular training.

Other variables such as the number of sprints performed, RPE and speed loss (FI) also showed relationships with blood lactate and ammonia \((r = 0.67 \text{ to } 0.87, \text{ Fig. 1})\). It is surprising that the CMJ height loss showed greater predictive power in terms of metabolic response than the performance impairment induced in the test (speed loss). A previous study also showed that the CMJ test is more repeatable and sensitive to neuromuscular fatigue than other jump and sprint tests \([9]\). Other authors also observed decreased jumping performance following a soccer-simulation protocol, despite participants maintaining their sprint performance \([23]\). Furthermore, it has been shown that sprint performance requires a much shorter restoration time compared to CMJ performance \([9]\). An alternative method based on subjective perceived exertion during the training session (RPE) has recently attracted considerable attention \([29]\). It is non-invasive, low-cost and easy to use. RPE was expected to rise throughout the sprints, as previous studies have shown that RPE increases as the total amount of work increases \([29]\). The very large relationships observed between RPE and blood lactate \((r = 0.87)\) and ammonia \((r = 0.85)\) indicate that the RPE method might be a valuable tool to allow coaches to monitor the training load during sprint training. However, jumping technique is probably a more common and repeatable skill, whereas RPE reporting is highly variable based on athlete experience and familiarity with the scale.

In conclusion, the use of a simple and non-fatiguing test such as CMJ could help us monitor sprint training sessions without the need to measure blood lactate or ammonia concentrations, and would be more accurate than recording sprint times. Thus, CMJ could be a very useful and robust indirect measure of fatigue. Furthermore, the introduction of new field devices provides more practical ways of measuring jump height in the field \([28]\). A recent study has shown high reliability and excellent agreement between CMJ height measured using a force platform for an iPhone application (“My Jump” app ©) \([2]\). Therefore, a simple CMJ assessment using the My Jump app could be a low cost, easy-to-use application to assess fatigue during sprint training and individualize training regimes accordingly. Other variables such as the number of sprints performed, RPE or speed loss might also be used, although the estimation power is likely to be lower. Therefore, jump-based measurements during training may lead to a more accurate setting of training loads in sprint training sessions, by using an individualized sprint dose based on a mechanical and physiological response rather than a standard fixed number of sprints for all athletes. This method would provide more detailed and scientific information about the actual level of fatigue as computed during a sprint training session, using only changes in CMJ height, and could be of considerable benefit to coaches and athletes. This study may provide insight into the results illustrated in previous studies, and in field conditions it may be a first step toward the development of specific and individualized sprint training for high-level sprinters training under field conditions.

Acknowledgements

We are very grateful to the athletes of the AAC Track and Field club for their involvement in the protocol and Sebastian Conesa (Sprint Coach). The authors sincerely thank Dr. JB Morin (University of Nice, France) for his helpful and stimulating comments on this work and on the present article. We also gratefully thank the 2 anonymous reviewers for their supportive and constructive comments. No sources of funding were used in the preparation of this article.

Conflict of interest: The authors declare no conflict of interest.
References


