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Characteristics Explaining Performance in Downhill Mountain Biking

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Purpose: To identify physiological, psychological, and skill characteristics that explain performance in downhill (DH) mountain-bike racing. ***Methods:*** Four studies were used to (1) identify factors potentially contributing to DH performance (using an expert focus group), (2) develop and validate a measure of rider skill (using video analysis and expert judge evaluation), (3) evaluate whether physiological, psychological, and skill variables contribute to performance at a DH competition, and (4) test the specific contribution of aerobic capacity to DH performance. ***Results:*** Study 1 identified aerobic capacity, handgrip endurance, anaerobic power, rider skill, and self-confidence as potentially important for DH. In study 2 the rider-skill measure displayed good interrater reliability. Study 3 found that rider skill and handgrip endurance were significantly related to DH ride time (β = –0.76 and –0.14, respectively; R^2 = .73), with exploratory analyses suggesting that DH ride time may also be influenced by self-confidence and aerobic capacity. Study 4 confirmed aerobic capacity as an important variable influencing DH performance (for a DH ride, mean oxygen uptake was 49 ± 5 $mL \cdot kg^{-1} \cdot min^{-1}$, and 90% of the ride was completed above the 1st ventilatory threshold). ***Conclusions:*** In order of importance, rider skill, handgrip endurance, self-confidence, and aerobic capacity were identified as variables influencing DH performance. Practically, this study provides a novel assessment of rider skill that could be used by coaches to monitor training and identify talent. Novel intervention targets to enhance DH performance were also identified, including self-confidence and aerobic capacity.

Keywords: bicycling, exercise tests, hand strength, physical endurance, self-confidence

Mountain biking is a form of off-road cycling that is popular as a recreational activity worldwide.[1] Competitive downhill mountain-bike racing is experiencing a particularly rapid growth; the number of competitive events worldwide increased from 23 in 2000 to 474 in 2013 to accommodate 67,000 competitors yearly.[2] Downhill mountain biking involves descending a trail in an individual time-trial format. Course requirements include sprint sections, corners, and coasting sections where riders negotiate a variety of natural and man-made obstacles such as rocks and jumps. Courses vary in length, but race times for the fastest riders typically range from 2 to 5 minutes.[3]

Reviews highlight a lack of understanding of the physiological and psychological requirements of this sport.[4,5] However, scientific study has been completed in the related disciplines of cross-country mountain biking, motocross, and off-road vehicle riding. Studies found that aerobic capacity,[4–6] anaerobic power,[7,8] dynamic skill, upper-body muscle function,[6,8–10] and anxiety control[11] are required to excel in those disciplines. Unfortunately, differences in event duration, the amount of self-propulsion required, the terrain that is used, and the objective risk between the disciplines make inferences from these other sports difficult. Meanwhile, downhill coaches focus on riding dynamics, strength, and power.[12] Furthermore, initial studies suggest that downhill competitors may have relatively high aerobic capacity,[13,14] and studies of recreational downhill mountain biking suggest a high aerobic demand of that discipline.[15] Downhill competitions also induce relatively high heart rate and cortisol responses[14] despite remarkably low propulsive cycling power output.[16] To date the role of rider skill and psychology has been largely ignored.

The aim of this multiple-study project was to determine key characteristics of downhill competitors and key requirements of the sport that explain performance in downhill. We hypothesized that rider skill would explain the majority of variance in performance in downhill but that physiological variables (such as aerobic capacity, lower-body anaerobic capacity, and handgrip endurance) and psychological variables (such as self-confidence), would also be identified as influential.

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Methods

Design

This 4-study article describes the following investigations: (1) a qualitative identification of variables of interest in performance in downhill, (2) development of a skill measure, (3) a field study characterizing 43 riders at a downhill competition, and (4) a laboratory study characterizing 10 riders during a simulated downhill competition. All studies were approved by the institutional ethics committee and conformed to the Declaration of Helsinki, and all participants provided written, informed consent.

Study 1: Qualitative Identification of Variables of Interest to Performance in Downhill. An expert panel comprised 1 team manager, 1 mechanic, 4 elite riders, and 1 sport scientist, which assembled at a round of the British Downhill Series (Nant Gwrtheyrn, March 22, 2011) with the aim to identify variables that are of particular relevance to performance in downhill.[17] This aim was met by the panel's completing an interview-guided needs analysis. An extensive list of possible variables was produced, ambiguous variables were precisely defined, duplicates were removed, and finally the variables were categorized into key areas.

To confirm the expert-panel findings and give an indication of the relative importance of the identified variables, a survey was then sent to 50 downhill riders of various abilities from the United Kingdom, the United States, and France. The riders were asked to rank the variables identified by the expert panel in order of perceived importance by assigning each variable on a scale of 1 to 6 (most to least important). Thirty-five surveys were returned (10 elite, 8 expert, 15 senior, and 2 junior), which equated to a 70% response rate.

Study 2: Skill-Measure Development. An expert panel of 3 highly experienced (>10 y practice) professional mountain-bike coaches was assembled at the UK National Downhill Championships (Llangollen, July 27, 2011) with the aim of generating a working definition of rider skill required for downhill. The following definition was agreed on: "The ability to dynamically balance the bike while generating or maintaining speed through pedaling and pressure control and while controlling speed over technically challenging terrain." To achieve this definition of high skill level in downhill, the coaches then identified a list of specific components that were required. A marking score sheet was generated: Each specific component was included to be scored from 0 (*skill not present*) to 10 (*skill could not be developed further*). An average score could then be calculated for each rider to define his or her overall skill level. To assess validity (interrater reliability) of this measure, 13 participants (downhill race experience 5 ± 3 y) from senior (n = 4), master (n = 4), expert (n = 2), and elite (n = 3) categories were filmed riding a 50-m section of the downhill course that was chosen due to its technically demanding nature (it included jumps or bumps, corners, and natural obstacles including roots or rocks). Three independent judges blinded to race results then reviewed the videos and used the marking criteria to determine skill level.

Study 3: Characteristics of Riders at a Downhill Competition. 43 male participants (age 25 ± 5 y, height 179 ± 7 cm, body mass 78 ± 8 kg, downhill race experience 6 ± 2 y) from the junior (n = 5), senior (n = 11), master (n = 9), expert (n = 6), and elite (n = 12) categories were recruited by self-selection convenience sampling at 2 repetitions of a UK regional downhill championship event (Llangynog, July 31, 2011, and July 15, 2012). Participants represented approximately 12%, 12%, 16%, 30%, and 57% of the total population attending the 2 events in the junior, senior, master, expert, and elite categories, respectively.

Testing was completed at the event, where environmental conditions were zero precipitation, a dry-to-damp track, and an air temperature that ranged from 12°C to 19°C. The downhill course was ~2 km in length with an altitude drop of 368 m and comprised classical downhill features, with a usual winning time of approximately 214 seconds. Time in seconds of the faster of 2 competitive rides was used as a dependent variable in analyses. To reduce intersubject variability due to equipment choice, inclusion criteria ensured that all bikes were of similar mass, age, and suspension travel.

Independent-variable outcome measures were selected based on results from studies 1 and 2 and practical restraints of field testing. Physiological variables included aerobic capacity, lower-body anaerobic capacity, and handgrip endurance, all of which were assessed before prerace practice (1 day before the participants' competitive timed attempts) in order of presentation. Aerobic capacity was estimated via the use of the Chester Step Test.[18] Although not a direct assessment of aerobic capacity in cycling, the test provided a practically implementable estimate of aerobic capacity that did not interfere with performance during the competitive event. Lower-body anaerobic capacity was assessed by 30-second Wingate Test completed on an ergometer (874E, Monark Exercise AB, Sweden). Resistance was not applied to the freewheel until the participants had attained maximum pedaling cadence, and average power output over the 30-second test[19] was used for all analyses. Handgrip endurance was measured using a calibrated Takei handgrip dynamometer (5001 Grip-A, Takei Scientific Instruments, Tokyo, Japan) as previously described.[20] Briefly, participants repeatedly contracted maximally and then relaxed for 5-second intervals (paced by an audible tone), with the average handgrip force elicited over a 5-minute period taken as handgrip endurance. Self-confidence was assessed within 1 hour before each participant's first timed ride to give an accurate measure of the prerace state. Ten items from the Competitive State Anxiety Inventory 2[21] were used to assess self-confidence. Rider skill was assessed by video analysis of each participant's fastest ride through a particular section of the course by an expert judge blinded to race results using the novel skill assessment detailed in study 2.

Study 4: Characterization of Riders in a Laboratory and During a Simulated Competition Downhill Ride. 10 male participants (age 22.2 ± 4.5 y, height 178 ± 5 cm, body mass 72 ± 8 kg, downhill racing experience 7 ± 3 y) from the senior (n = 7), expert (n = 1), and elite (n = 2) categories were selected by convenience sampling. Testing was completed off-season between November 1 and December 21, 2009.

Testing comprised 2 visits: a laboratory assessment and a simulated competition ride on a downhill British Downhill Series course (Nant Gwrtheyrn), separated by 2 weeks. In the laboratory, maximal oxygen uptake (VO_{2max}) and ventilatory thresholds were determined during an incremental exercise to exhaustion test with a verification stage on an electronically braked cycle ergometer (Excalibur, Lode, Netherlands). Participants completed a 5-minute warm-up at 100 W. After 2 minutes of unloaded cycling, the test then started at 100 W. Participants were required to maintain a cadence of 70 rpm. Using a ramped protocol, the power output was increased linearly to provide a 1-W increase every 5 seconds (36 W every 3 min). The test was terminated on voluntary exhaustion or failure to maintain the required cadence for a period of 10 seconds. A verification stage was completed whereby participants completed an exercise stage at a work rate 36 W higher than in the previously completed stage. This process was repeated until the increase in VO_{2max} was <2%. Both rating of perceived exertion (15-point 6–20 scale) and heart rate (S810i, Polar, Kempele, Finland) were recorded in the last 15 seconds of each stage. Expired respiratory gases were measured throughout using a portable calibrated online breath-by-breath automated gas analyzer (Metamax 3B, Cortex, Leipzig, Germany).

At the downhill mountain-bike course, environmental conditions were zero precipitation, a dry track, and an air temperature that ranged from 1°C to 6°C. The course was of national championship standard, with a length of ~1 km and an altitude drop of 200 m and comprising classical downhill features, with a usual winning time on this course of approximately 135 seconds. To reduce intersubject variability due to equipment choice, inclusion criteria ensured that all bikes were of similar mass, age, and suspension travel. Immediately before testing, participants warmed up for 5 minutes using their usual preferred method (in all participants this was gentle cycling, completing minisprints, and moving the bike around to use upper-body muscles). Resistance to handgrip fatigue in response to the ride was then assessed for the dominant hand using a dynamometer (5001 Grip-A, Takei Scientific Instruments, Tokyo, Japan). Immediately preride and postride, participants completed 3 maximal contractions separated by 1 minute, the greatest of which was recorded and used to determine the percentage decrement in handgrip force in response to the ride. A handlebar-mounted stopwatch (DMC Sports Timer, Diverse Suspension Products, Valencia, CA) was used to record ride time. Throughout the ride participants wore a heart-rate monitor, and expired gases were collected using a gas analyzer (materials and methods as noted herein).

Statistical Analyses

All parametric data were analyzed by statistical software (version 20, SPSS, IBM, Armonk, New York, USA) and are presented as means ± SD. Statistical significance was set at $P < .05$.

Study 2 Statistical Analyses

To assess interrater reliability of the novel skill measure, an intraclass correlation coefficient (ICC_{3k}) was calculated between independent judges. Mean bias (by the Bland and Altman method) and 95% confidence interval of the bias were also calculated, as was standard error of the measurement.

Study 3 Statistical Analyses

As data were collected over a 2-year period, race times for each year were standardized using z-scores. A structural-equation-modeling approach determined variables associated with performance, using the nonparametric partial-least-squares method (PLS, SmartPLS version 2.0 [M3] Beta, Hamburg, Germany), which is particularly suited to small sample sizes,[22] as well as factor loadings and standardized regression coefficients. PLS generates t-values from a bootstrapping procedure (5000 iterations). The PLS model determined the validity, internal consistency, and convergent validity of the self-confidence measurement, whereby loadings >0.4,[23] composite reliability >0.7,[24] and average variance extraction >0.5,[24] respectively, are considered acceptable. Then the PLS model was used to test whether the independent factors of lower-body aerobic and anaerobic capacity, handgrip endurance, self-confidence, and skill could explain significant variance in race performance by examining the standardized path coefficients (β) and the total variance explained by the model (R^2, with .02, .15, and .35 being interpreted as small, medium, and large effects, respectively).[25]

Study 4 Statistical Analyses

For laboratory testing, the anaerobic threshold and the respiratory compensation point were identified from the first and second ventilatory thresholds by blinded V-slope method,[26] with other variables calculated as an average of the final 10 seconds before exhaustion. For field testing, exercise intensity of completing a downhill ride was described by graphical presentation of VO_2 and heart rate and allocation of individual data points to 1 of 4 exercise-intensity zones: below the first ventilatory threshold, above the first but below the second ventilatory threshold, above the second ventilatory threshold but below VO_{2max}, and above laboratory-determined VO_{2max}. Percentage of ride time spent in each intensity zone could then be calculated. Data recorded preride and postride (handgrip force) were analyzed using paired-samples t-tests. Effect size for independent t-tests was calculated as Cohen d and interpreted as no effect (<0.2), small effect (0.2–0.5), medium effect (0.5–0.8), or large effect (>0.8).[27] Physiological variables were correlated with each other by Pearson product–moment correlation coefficient (r) and with ranking (ride time) by Spearman rank correlation coefficient (ρ).

Results

Study 1 Results

The key areas particularly relevant to performance in downhill as identified by the expert panel and then confirmed by a survey of downhill riders are presented in Table 1 (in order of importance).

Study 2 Results

The specific components identified by the coaches as required for skilled performance in downhill are presented in Table 2. When the expert judges independently used the novel skill measure they showed substantial agreement with one another, as verified by an intraclass correlation coefficient (ICC_{3k}) of .87, a mean bias [95% confidence interval] of –0.57 [–1.37 to 2.69] arbitrary units, and a standard error of the measurement of 0.57 arbitrary units.

Study 3 Results

Mean ride time was 214 ± 34 seconds. Independent outcome variables (physiological, psychological, and skill measures) are presented in Table 3. Using PLS, the analysis of the self-confidence measurement model showed that all factor loadings

Table 1 Variables Identified as Particularly Important for Performance in Downhill Mountain Biking

Rank	Variable	Average rank score	SD
1	Technical skill	1.6	0.8
2	Self-confidence	2.0	1.0
3	Aerobic capacity	3.3	1.0
4	Lower-body anaerobic capacity and upper-body muscle function	4.5	1.2
5	Bike setup	4.7	1.0
6	Past experience	5.0	1.3

Note: Variables were selected by an expert panel (N = 7) and then placed in rank order of perceived importance by mixed-ability (amateur to pro elite) downhill mountain-bike riders (N = 35). Perceived importance was rated on a scale of 1–6 (most to least important).

Table 2 Assessment Criteria for Determining Skill Level With a Suggested Score Sheet

Assessment criterion	Circle score (from 0, *skill not present,* to 10, *skill could not be developed further*)									
Body position	1	2	3	4	5	6	7	8	9	10
Footwork	1	2	3	4	5	6	7	8	9	10
Focal point	1	2	3	4	5	6	7	8	9	10
Speed control	1	2	3	4	5	6	7	8	9	10
Energy management	1	2	3	4	5	6	7	8	9	10
Pressure control	1	2	3	4	5	6	7	8	9	10
Fluidity and line choice	1	2	3	4	5	6	7	8	9	10
Average score (sum of scores ÷ 7)										

Note: Riders should be assessed on a technically demanding section of the course, including jumps/bumps, corners, and natural obstacles including roots/rocks. Definition of skill: the ability to dynamically balance the bike, while generating or maintaining speed through pedaling and pressure control and while controlling speed over technically challenging terrain. Definition of pressure control: the ability to select the appropriate response of absorbing or resisting terrain-induced forces acting on the bike. For definitions of specific assessment criteria please contact the authors.

Table 3 Physiological, Psychological, and Skill-Level Outcome Measures Obtained From 43 Mixed-Ability Downhill Mountain Bikers at a Downhill Competition

Variable	Mean ± SD
Aerobic capacity (estimated maximal oxygen uptake) $mL \cdot kg^{-1} \cdot min^{-1}$	50.5 ± 14.6
Anaerobic capacity (W)	704 ± 93
Handgrip endurance (kg)	41.6 ± 8.1
Self-confidence (10–40)	30.1 ± 5.2
Skill level (judges score 0–10)	7.4 ± 1.7

Note: For self-confidence and skill a higher score suggests a better level. See Methods for further explanation of how outcome measures were obtained.

were >0.40, composite reliability was >0.89, and average variance extraction was 0.52. Bootstrapping revealed all indicators of the latent variable to be significant ($P < .001$) (Figure 1). When determining which outcome measures were related to performance, the structural model explained 73% of variance in race time (large effect size). However, only 2 of the variables were significantly related to race performance: skill level and handgrip endurance. Aerobic capacity, lower-body anaerobic capacity, and self-confidence were not significantly related to performance (Figure 1).

Study 4 Results

Mean ride time was 146 ± 27 seconds. Physiological data collected during the laboratory and simulated ride are shown in Table 4. Peak values obtained during the simulated ride were less than the laboratory-obtained maximal values for VO_2, minute ventilation, and heart rate (92%, 88%, and 95% of maximal values, respectively) but more for peak breathing frequency (115%).

VO_2 during the simulated ride compared with maximal aerobic capacity assessed during laboratory testing is shown in Figure 2. Mean VO_2 was 45.9 ± 5.3 $mL \cdot kg^{-1} \cdot min^{-1}$, which was 81% ± 5% of laboratory-determined VO_{2max}. Regarding data collected, once steady state had been achieved, mean VO_2 increased slightly to 49.1 ± 4.9 $mL \cdot kg^{-1} \cdot min^{-1}$, which was 86% ± 6% of laboratory-determined VO_{2max}. Mean minute ventilation was

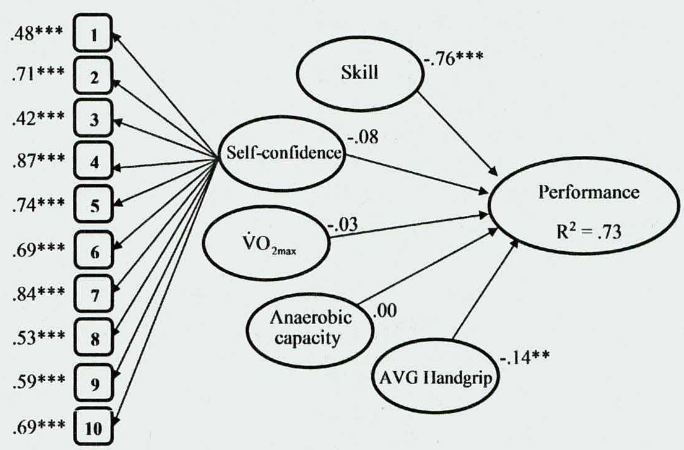

Figure 1 — Outcome measures (independent variables) related to performance (dependent variable) in downhill mountain biking. The model was generated by partial least-squares analysis and boot-strapping procedures (**$P < .01$, ***$P < .001$). Numbers 1 to 10 refer to the 10 items of the Competitive State Anxiety Inventory 2. Left-pointing arrows denote the factor loadings of the self-confidence measurement model, and right-pointing arrows denote the path coefficients (β) of the structural model. Note that negative correlations were present because performance was measured by time (a shorter time indicated better performance). The total variance explained by the model can be calculated from R^2 (73%). Abbreviations: VO_{2max}, maximal oxygen uptake; AVG, average.

Table 4 Physiological Parameters of 10 Downhill Mountain Bikers Completing a Laboratory-Based Cycle-Ergometer Test and During a Simulated Competition Downhill Ride, Mean ± SD

Variable	Laboratory-testing maximal values	Downhill-ride peak values
VO_2 (mL · kg^{-1} · min^{-1})	57.9 ± 6.1	53.5 ± 4.7
Minute ventilation (L/min)	141 ± 19	124 ± 19
Breathing frequency (breaths/min)	53 ± 8	61 ± 7
Heart rate (beats/min)	192 ± 5	182 ± 6
Peak power output (W)	299 ± 52	N/A
Peak power output (W/kg)	4.1 ± 0.7	N/A
First ventilatory threshold (mL · kg^{-1} · min^{-1})	45 ± 6	N/A
First ventilatory threshold (%VO_{2max})	78 ± 7	N/A
First ventilatory threshold (W)	201 ± 35	N/A
Heart rate at first ventilatory threshold (beats/min)	164 ± 18	N/A
Second ventilatory threshold (mL · kg^{-1} · min^{-1})	51 ± 6	N/A
Second ventilatory threshold (%VO_{2max})	88 ± 6	N/A
Second ventilatory threshold (W)	236 ± 52	N/A
Heart rate at second ventilatory threshold (beats/min)	174 ± 12	N/A

Note: Ventilatory thresholds calculated using the V-slope method.[4] N/A indicates data not determined during the downhill ride. Abbreviation: VO_{2max}, oxygen uptake.

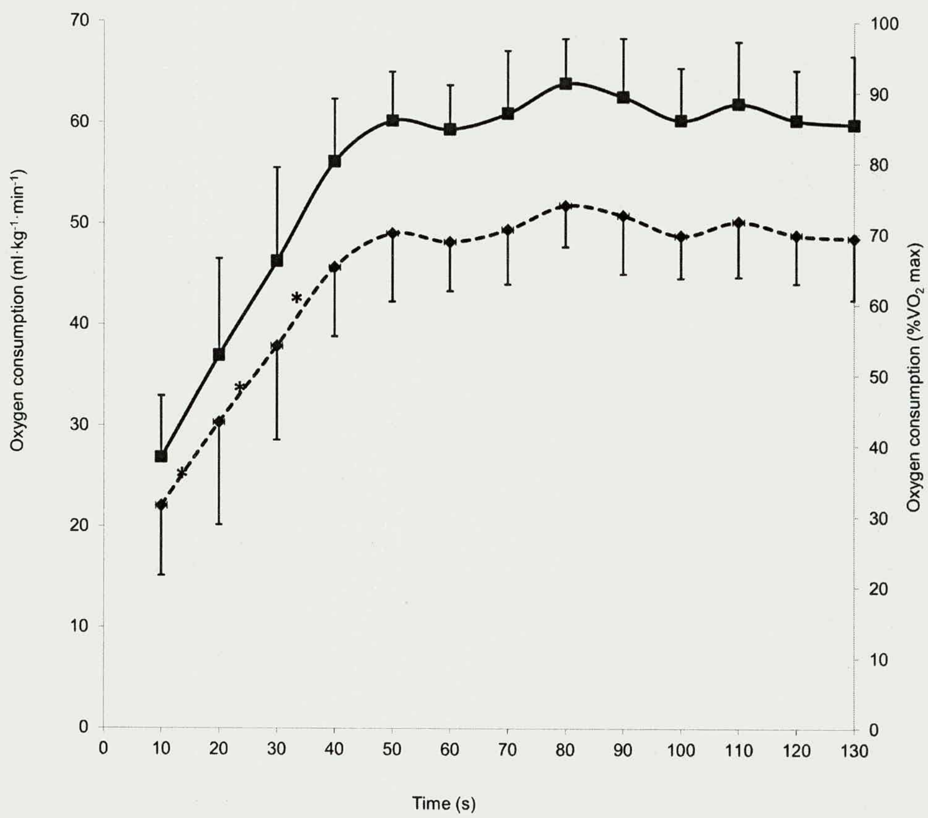

Figure 2 — Oxygen consumption during descent in a downhill mountain-bike course. Data are means ± SD. Dashed line indicates absolute oxygen uptake; Solid line indicates oxygen consumption relative to laboratory-determined maximal oxygen uptake. *Significantly different from 130-second data point by repeated-measures analysis of variance and Tukey post hoc test. Thus, steady state was achieved after 40 seconds (there was no change [$P > .05$] in oxygen uptake between 40 and 130 seconds).

108.8 L/min (77% ± 10% of laboratory-determined maximum), mean breathing frequency was 52 ± 6 breaths/min (98% ± 9% of laboratory-determined maximum), and mean heart rate was 177 ± 7 beats/min (92% ± 2% of laboratory-determined maximum). Figure 3 shows the proportion of the downhill ride expressed as relative exercise intensity (%VO_{2max} and % maximal heart rate). According to analysis of VO_2 (expressed as individual data points), relative time spent below the first ventilatory threshold was 10% ± 18%, between the first and second ventilatory thresholds was 47% ± 31%, between the second ventilatory threshold and VO_{2max} was 34% ± 33%, and above laboratory-determined VO_{2max} was 9% ± 15%.

Handgrip fatigue occurred in response to the ride, with handgrip force significantly decreasing by 22% between preride and postride assessments (524 ± 68 vs 409 ± 71 N, $t = 7.55$, $P = .001$, $d = 1.3$). A modest but significant positive correlation was observed between handgrip fatigability (the percentage decrement in handgrip force) and the rank order of ride time (Spearman rank-order correlation coefficient = .71, $P = .02$), suggesting that faster riders had less handgrip fatigue. In contrast, no cardiovascular variables were correlated with ranking.

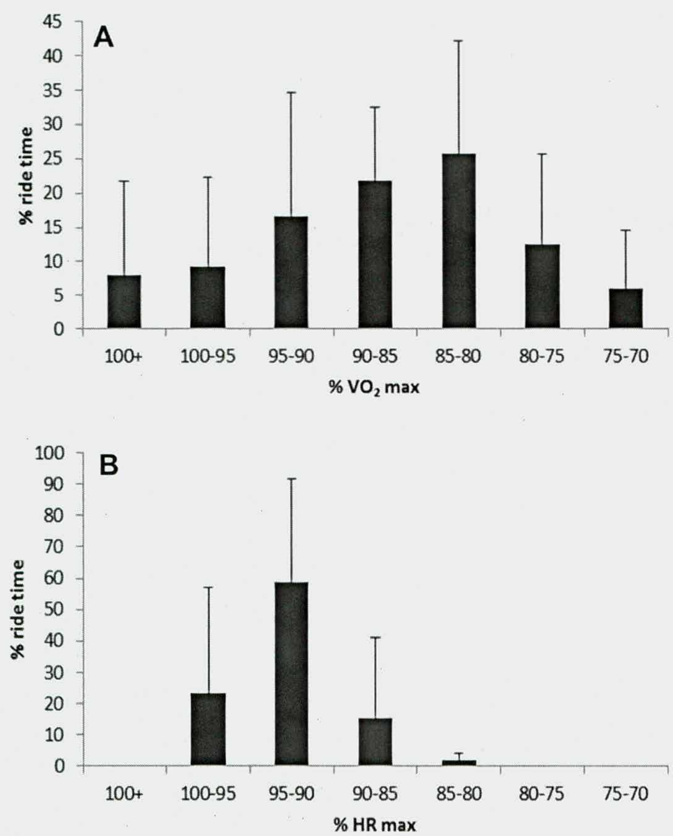

Figure 3 — Time during a simulated competition downhill ride spent at specific exercise intensities. Data are means ± SD and include the steady-state period of the ride only. (A) Maximal oxygen uptake (VO2 max) during the downhill ride expressed as a %VO2max as determined during laboratory testing. (B) Maximal heart rate (HR max) during the downhill ride expressed as a percentage of HR max as determined during laboratory testing

Discussion

We had hypothesized that a number of variables were of importance to downhill performance, including rider skills, psychological factors, and aerobic capacity, which to date have generally been ignored. An expert panel and a survey of downhill riders confirmed the perceived importance of these hypothesized variables. Specifically, skill, self-confidence, aerobic capacity, lower-body anaerobic power, handgrip endurance, bike setup, and past experience were suggested to be important for downhill performance. Consistent with the expert panel's suggestions, follow-up studies in the field confirmed that skill and handgrip endurance could explain 73% of variance in downhill ride time at a downhill competition. A laboratory study and simulated competition further found that the physiological requirements of downhill events comprise a large aerobic component. However, lower-body anaerobic power and self-confidence did not explain downhill performance, at least in primary analyses.

As expected in such a technique-dependent discipline, skill explained most of the variance in downhill performance. The next-most-consistent performance predictor was handgrip endurance. This may be due to better riders having developed greater upper-body muscle endurance. Indeed, in study 3 a relationship between handgrip endurance (that was assessed before any riding took place) and performance was identified. Alternatively, better riders may have tackled terrain with greater efficiency or increased confidence allowing a more relaxed grip. In study 4 a relationship between handgrip fatigability (that was assessed by decrement in handgrip force over a ride) and performance was identified.

A role for aerobic capacity in performance is partially supported by the current data. Despite a lack of a direct relationship between aerobic capacity and performance being identified in study 3, which is in contrast to previous studies on motocross riders,[6] we still observed a high aerobic demand of the sport. In study 4, VO_2 during the simulated downhill competition was 86% of the participants' maximal aerobic capacity. Furthermore, 90% of downhill ride time was completed above the first ventilatory threshold and 43% of downhill ride time was completed above the second ventilatory threshold. This is despite mean power output as assessed by power meter at the crank being only 9% of peak values in downhill, and pedaling periods making up only 55% of total ride time.[16] The proportion of ride time spent at higher exercise intensities was greater than that observed previously in simulated recreational downhill mountain biking.[15] Note also that predicted (study 3) and actual (study 4) maximal aerobic capacity were 51 and 58 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively, a finding supported by others.[13] It is likely that such high aerobic demand is due to the contribution of the upper-body work required to stabilize the bike.[8,15] The high breathing frequency observed in study 4 may be due to a superficial breathing pattern and use of the Valsalva maneuver to stabilize the spine during large ground-reaction forces.[6]

Self-confidence was not related to performance in the primary analysis of study 3. However, self-confidence was ranked as the second-most important variable in study 1, and previously athletes' skill level has been shown to influence self-confidence.[28] Consequently, the analysis model was respecified so that skill loaded onto self-confidence and self-confidence loaded onto performance (Figure 4). In this post hoc analysis, the variance explained by the new model (35%, large effect size) was reduced. However, in contrast to the first model, skill loaded through self-confidence, and thus the relationship between self-confidence and performance was strengthened and significant (Figure 4). Furthermore, in this

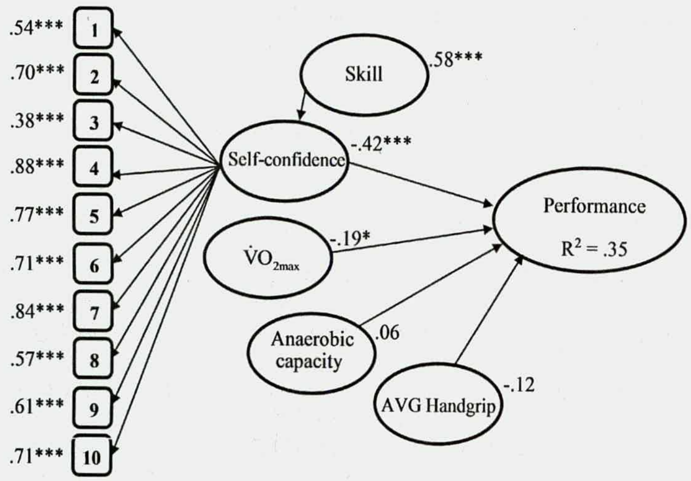

Figure 4 — Outcome measures (independent variables) related to performance (dependent variable) in downhill mountain biking using an alternative structural model with skill loaded through self-confidence. The model was generated by partial least-squares analysis and boot-strapping procedures (**$P < .01$, ***$P < .001$). Numbers 1 to 10 refer to the 10 items of the Competitive State Anxiety Inventory 2. Left-pointing arrows denote the factor loadings of the self-confidence measurement model, and right-pointing arrows denote the path coefficients (β) of the structural model. Note that negative correlations were present because performance was measured by time (a shorter time indicated better performance). The total variance explained by the model can be calculated from R^2 (35%). Abbreviations: VO_{2max}, maximal oxygen uptake; AVG, average.

post hoc analysis aerobic capacity was significantly related to performance, too.

Conversely, maximal anaerobic power was unrelated to performance and remained unrelated in post hoc analyses. It is possible that a measure of ability to repeatedly produce anaerobic efforts may better correlate with performance in downhill, as shown previously in cross-country mountain biking.[7]

Practical Applications

Before the relative contribution of factors influencing downhill performance could be investigated, a measure of skill was required. Skill was successfully defined, and the developed measure could be independently rated with acceptable agreement between judges. Thus, this study offers a new assessment of skill in downhill that may be useful for talent identification and team selection and as an outcome measure to monitor success of skill training. Although an expert is required, video analysis allows offline assessment. Other practical advice concerning the outcome measures used herein concerns the assessment of cardiovascular demand in downhill. This study and others[15] suggest that heart rate should be used cautiously, as it will overestimate VO_2 (Figure 3).

This study also identified targets suitable for intervention to enhance downhill performance. Riders should continue to focus on skill development, but physiological variables should not be ignored, particularly development of handgrip endurance and aerobic capacity (using muscle groups of the whole body, not just the legs). Coaching styles should also use strategies to enhance riders' self-confidence to enable physiological potential to be fully used.

Limitations of our study include the use of a qualitative method to develop a definition of skill in study 1. Despite a broad spectrum of experts being included in the focus group, the definition is likely to cause debate. In field study 3, a nonspecific estimate of maximal aerobic capacity and only 1 simple measure of self-confidence was used. Readers should thus use caution when comparing aerobic-capacity results between studies 3 and 4. Also, despite recruiting the majority of the population available, the sample size was relatively small and homogeneous. Nevertheless, characteristics were identified that were statistically related to performance. In study 4 we used VO_2 to measure exercise intensity. This method overcomes problems of using heart rate, which is artificially influenced by isometric contractions[9,10] and psychoemotional factors in downhill.[29] Indeed, dissociation between heart rate and VO_2 was observed in the current study (Figure 3). Still, we did not measure excess postexercise VO_2 and so could not determine total energy expenditure. Despite these limitations, the use of a 4-study design provides consistent support for this study's conclusions. Future studies should address these limitations, attempt to account for the remaining 27% unexplained variance in downhill performance identified herein, and complete intervention studies to experimentally determine whether this study's targets can influence downhill performance.

Conclusions

Using data from focus groups, surveys, observational field studies, and laboratory and simulated competition testing, the variables of rider skill, handgrip endurance, self-confidence, and aerobic capacity (tentatively presented in order of importance) were identified as characteristics explaining performance in downhill mountain biking.

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References

1. Baron R. Aerobic and anaerobic power characteristics of off-road cyclists. *Med Sci Sports Exerc*. 2001;33:1387–1393. PubMed doi:10.1097/00005768-200108000-00022
2. *Roots and Rain Event List*. Cardiff, UK: Roots and Rain. www.rootsandrain.com/races.html?all. Accessed March 21, 2014.
3. *UCI Cycling Regulations, Part 4: Mountain Bike Races*. Aigle, Switzerland: Union Cycliste Internationale. http://www.uci.ch/mm/Document/News/Rulesandregulation/16/72/76/MTBReglementsENG_English.pdf. Accessed March 25, 2014.
4. Atkinson G, Davison R, Jeukendrup A, Passfield L. Science and cycling: current knowledge and future directions for research. *J Sports Sci*. 2003;21:767–787. PubMed doi:10.1080/0264041031000102097
5. Impellizzeri FM, Marcora SM. The physiology of mountain biking. *Sports Med*. 2007;37:59–71. PubMed doi:10.2165/00007256-200737010-00005
6. Burr JF, Jamnik VK, Shaw JA, Gledhill N. Physiological demands of off-road vehicle riding. *Med Sci Sports Exerc*. 2010;42:1345–1354. PubMed doi:10.1249/MSS.0b013e3181cd5cd3
7. Inoue A, Sa Filho AS, Mello FC, Santos TM. Relationship between anaerobic cycling tests and mountain bike cross-country performance. *J Strength Cond Res*. 2012;26:1589–1593. PubMed

8. Konttinen T, Kyröläinen H, Häkkinen K. Cardiorespiratory and neuromuscular responses to motocross riding. *J Strength Cond Res*. 2008;22:202–209. PubMed doi:10.1519/JSC.0b013e31815f5831
9. Cable T. Cardiovascular function. In: Eston R, Reilly T, eds. *Kinanthropometry and Exercise Physiology Laboratory Manual: Tests, Procedures and Data*. Vol 1. 3rd ed. London: Routledge; 2008:117–133.
10. Louhevaara V, Smolander J, Aminoff T, Korhonen O, Shen N. Cardiorespiratory responses to fatiguing dynamic and isometric hand-grip exercise. *Eur J Appl Physiol*. 2000;82:340–344. PubMed doi:10.1007/s004210000200
11. Demojà CA, Demoja G. State-trait anxiety and motocross performance. *Percept Mot Skills*. 1986;62:107–110. PubMed doi:10.2466/pms.1986.62.1.107
12. Rhyan S. Training suggestions for the downhill mountain bike racer. *Strength Cond J*. 2005;27:42–45. doi:10.1519/00126548-200510000-00006
13. Dal Monte A, Faina M. *Valutazione dell'atleta. Analisi funzionale e biomeccanica della capacità di prestazione*. Turin, Italy: UTET; 1999:372–376.
14. Sperlich B, Achtzehn S, Buhr M, Zinner C, Zelle S, Holmberg H. Salivary cortisol, heart rate, and blood lactate responses during elite downhill mountain bike racing. *Int J Sports Physiol Perform*. 2012;7(1):47–52. PubMed
15. Burr JF, Drury CT, Ivey AC, Warburton DE. Physiological demands of downhill mountain biking. *J Sports Sci*. 2012;30:1777–1785. PubMed doi:10.1080/02640414.2012.718091
16. Hurst HT, Atkins S. Power output of field-based downhill mountain biking. *J Sports Sci*. 2006;24:1047–1053. PubMed doi:10.1080/02640410500431997
17. Sofaer S. Qualitative methods: what are they and why use them? *Health Serv Res*. 1999;34:1101–1118. PubMed
18. Sykes K, Roberts A. The Chester Step Test—a simple yet effective tool for the prediction of aerobic capacity. *Physiotherapy*. 2004;90:183–188. doi:10.1016/j.physio.2004.03.008
19. Bar-Or O. The Wingate anaerobic test an update on methodology, reliability and validity. *Sports Med*. 1987;4:381–394. PubMed doi:10.2165/00007256-198704060-00001
20. Macdonald JH, Callender N. Athletic profile of highly accomplished boulderers. *Wilderness Environ Med*. 2011;22:140–143. PubMed doi:10.1016/j.wem.2010.11.012
21. Martens R, Burton D, Vealey RS, Bump LA, Smith DE. Development and validation of the Competitive State Anxiety Inventory-2. In: Martens R, Vealey RS, Burton D, eds. *Competitive Anxiety in Sport*. Champaign, IL: Human Kinetics; 1990:117–190.
22. Chin WW. The partial least squares approach to structural equation modeling. *Mod Meth Bus Res*. 1998;295:295–336.
23. Hulland J. Use of partial least squares (PLS) in strategic management research: a review of four recent studies. *Strateg Manage J*. 1999;20:195–204. doi:10.1002/(SICI)1097-0266(199902)20:2<195::AID-SMJ13>3.0.CO;2-7
24. Fornell C, Larcker DF. Evaluating structural equation models with unobservable variables and measurement error. *J Mark Res*. 1981;18(1):39–50. doi:10.2307/3151312
25. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum; 1988.
26. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol*. 1986;60:2020–2027. PubMed
27. Cohen J. A power primer. *Psychol Bull*. 1992;112:155–159. PubMed doi:10.1037/0033-2909.112.1.155
28. Perry JD, Williams JM. Relationship of intensity and direction of competitive trait anxiety to skill level and gender in tennis. *T Sport Psychol*. 1998;12(2):169–179.
29. Odaglia G, Magnano G. Heart activity in motocross [article in Italian]. *Med Sport*. 1979;32:199–206.