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REVIEW ARTICLE

Relationship of Anthropometric and Training Characteristics with Race Performance in Endurance and Ultra-Endurance Athletes

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Abstract

A variety of anthropometric and training characteristics have been identified as predictor variables for race performance in endurance and ultra-endurance athletes. Anthropometric characteristics such as skin-fold thicknesses, body fat, circumferences and length of limbs, body mass, body height, and body mass index were bi-variately related to race performance in endurance athletes such as swimmers in pools and in open water, in road and mountain bike cyclists, and in runners and triathletes over different distances. Additionally, training variables such as volume and speed were also bi-variately associated with race performance. Multi-variate regression analyses including anthropometric and training characteristics reduced the predictor variables mainly to body fat and speed during training units. Further multi-variate regression analyses including additionally the aspects of previous experience such as personal best times showed that mainly previous best time in shorter races were the most important predictors for ultra-endurance race times. Ultra-endurance athletes seemed to prepare differently for their races compared to endurance athletes where ultra-endurance athletes invested more time in training and completed more training kilometers at lower speed compared to endurance athletes. In conclusion, the most important predictor variables for ultra-endurance athletes were a fast personal best time in shorter races, a low body fat and a high speed during training units.

Key Words: Swimming; Cycling; Running; Skin-Fold; Body Fat; Ultra-Endurance

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INTRODUCTION

In endurance and ultra-endurance athletes, a variety of different anthropometric characteristics (*i.e.* body mass, body fat, skin-fold thicknesses, body height, length and circumferences of limbs), training characteristics (*i.e.* speed during training units, duration of training units, training volume) and physiological variables (*i.e.* maximum oxygen uptake, anaerobic threshold, lactate threshold, ventilatory threshold) have been identified as important predictor variables for race performance.

In contrast to an endurance performance, an ultra-endurance performance is defined as an event exceeding six hours in duration [1]. These longer events rely particularly on long-term preparation, sufficient nutrition, accommodation of environmental stressors, and psychological toughness [1]. Ultra-endurance races such as ultra-swimming [2-5], ultra-cycling [6-8], ultra-running [9-15] and the combination of these disciplines in multi-sports disciplines such as duathlon [16] and triathlon [17] have become of increasing popularity in recent decades.

This narrative review intends to focus on the association between anthropometric and training characteristics with ultra-endurance race performance. A literature search was performed in PUBMED (http://www.ncbi.nlm.nih.gov/pubmed/) using the terms 'anthropometry', 'training', 'performance', 'endurance', 'ultra', and 'athlete' by the end of April

2013. All resulting papers were searched for related citations. The following anthropometric characteristics such as single skin-fold thickness [18-25] , the sum of skin-fold thicknesses [18-54], the circumferences of limbs [21-27,29,31-33,35,37-39,50-52,55-61], the length of limbs [29-33, 36,46,48,50,54,59,61-63], body mass [19-23,26,29,31-33,36-39,42,45,48,50-54,57,59-61,64-71], body height [22,23,25-27,29-33,36,46-51,56,59-63,67,71-74], body mass index [19-23,25-27, 29,31-33,36,37,39,44,46,50-57,59-62,65,66,71,75], and percent body fat [9,19-27,29,31-34,36-39,40,44-48,50-54,56,58-61,65,66,76-81] were considered. Based upon these results, the aspects of training and previous experience were also included. Results of bi- and multi-variate analyses were presented in details.

ANTHROPOMETRIC CHARACTERISTICS

Anthropometric characteristics have been reported to affect endurance and ultra-endurance performance. Several studies investigated the relationship between specific anthropometric characteristics such as single skin-fold thicknesses and the sum of skin-fold thicknesses [18-54], circumferences of limbs [21-27,29,31-33.35,37-39,50-52,55-61], length of limbs [29,31,33,36,46,48,50,54,59,61-63], body mass [19,20,22,23,26,29,31-33,36,37,39,42,45,46,48,50-54,57,59-61,64-71], body height [22,23,25-27,29,31,33,36,46,48,50,51,56,59-63,67,71-74], body mass index [19,20,22,23,29,25-27,31-33,36,37,39,44,46,50-52,54,56,57,59-62,65,66,71,75], and percent body fat [9,19,20,22,23.25-27,29,31-34,36-39,40,44-48,50-54,56,58,59-61,65,66,76-81] with endurance performance in bi-variate analyses.

Single Skin-Fold Thicknesses at Upper and Lower Body

In 2006, Arrese and Ostariz investigated a potential association between single skin-fold thicknesses and race performance in high-level runners competing in races between 100m and 1,500m [18]. The most important finding was that specific single skinfold thicknesses at the lower limb were positively associated with running time over several distances, and the authors suggested that the determination of single skin-fold thicknesses might be a useful predictor of athletic performance. High correlations were found between the front thigh and the medial calf skinfolds and 1,500m run times, and between the front thigh and the medial calf skinfold thickness and 10,000m run times. In women, the front thigh and medial calf skinfolds were highly correlated with 400m run time. In men, however, the pectoral, suprailiacal, abdominal, biceps, triceps, subscapular skinfolds and the sum of six skinfolds were not associated with performance score for any of the distances.

Subsequent studies based upon these findings investigating a potential association between single skin-fold thicknesses and the sum of skin-folds in athletes competing over different distances and in different disciplines lead to disparate findings. Table 1 summarizes the associations between single skin-fold thicknesses and performance for female and male endurance and ultra-endurance athletes. For the upper body skin-folds at pectoral, mid-axilla, triceps and subscapular site, similar findings were reported. The pectoral, mid-axillar, triceps and subscapular site skin-fold thicknesses were related to race time in female [19,20] and male half-marathoners [21], in male marathoners [22,23], and in male 100-km ultra-marathoners [24]. However, pectoral, mid-axilla, triceps and subscapular skin-folds were not associated with performance in male ultra-marathoners such as multi-stage ultra-marathoners [25-28], and 24-hour ultra-marathoners [29,30]. Furthermore, pectoral skin-fold was not associated with race times in triathletes such as male multi-stage ultra-endurance triathletes [31], male Triple Iron ultra-triathletes [32], and female Ironman triathletes [33]. Also for male ultra-endurance cyclists, no correlation between race performance and pectoral, mid-axilla, triceps and subscapular skin-fold thickness existed [34].

For upper body skin-folds around the belly such as the abdominal and the suprailiacal skin-fold, the findings became different compared to the findings at pectoral, mid-axilla, triceps and subscapular site. The abdominal and suprailiacal skin-fold thicknesses were related to race time in runners such as female [19,20] and male [21] half-marathoners, male marathoners [22,23], male 100-km ultra-marathoners [24], and male Ironman triathletes [35], but not in male multi-stage ultra-

Table 1: Results of the bi-variate associations between single skin-fold thicknesses and race performance for female and male endurance and ultra-endurance athletes. The athletes are listed with increasing race distance or race duration

Variable	Pectoral	Mid-axilla	Triceps	Sub-scapular	Abdominal	Supra-iliacal	Thigh	Calf
Female half-marathoners	+	+	+	+	+	+		+
Male half-marathoners	+	+	+	+	+	+	−	−/+
Female marathoners							+	+
Male marathoners	+	+	+	+	+	+	+	+
Male long-distance inline skaters							+	+
Female Ironman triathletes	−				−	−	−	−
Male Ironman triathletes					+	+		
Male 100-km ultra-marathoners	+	+	+	+	+	+	+	+
Male multi-stage ultra-marathoners	−	−	−	−	−	−	−	−
Male 24-hour ultra-marathoners	−	−	−	−	−	−	−	−
Male ultra-endurance cyclists	−	−	−	−	−	−	−	−
Male Triple Iron ultra-triathletes	−				−	−	−	−
Male multi-stage ultra-triathletes	−				−	−	−	−

marathoners [25-28,36], male 24-hour ultra-marathoners [29,30], male ultra-endurance cyclists [34], male multi-stage ultra-endurance triathletes [31], male Triple Iron ultra-triathletes [32], and female Ironman triathletes [33].

For the lower body skin-folds at front thigh and medial calf site, the findings were again differently compared to the reports for upper body skin-folds. The front thigh skin-fold thickness was related to race time in female [37] and male [22,23] marathoners, in male 100-km ultra-marathoners [24,38], in male long-distance inline skaters [39], but not in male runners such as half-marathoners[35], multi-stage ultra-marathoners[25,26,28, 36], 24-hour ultra-marathoners [29,30], in triathletes such as male multi-stage ultra-endurance triathletes [31], male Triple Iron ultra-triathletes [32], female Ironman triathletes [33], and in male ultra-endurance cyclists [34]. The calf skin-fold thickness was related to race time in runners such as female [19,20] and male [21] half-marathoners, female [37] and male [22,23,40] marathoners, male 100-km ultra-marathoners [24], male long-distance inline skaters [39], but not in runners such as male multi-stage ultra-marathoners [25,26,28,36], 24-hour ultra-marathoners [29,30], in triathletes such as male multi-stage ultra-endurance triathletes [31], male Triple Iron ultra-triathletes [32], female Ironman triathletes [33], and in male ultra-endurance cyclists [34].

The Association of Sums of Skin-Folds with Endurance Performance

Apart from single skin-fold thicknesses, also the sum of skin-folds has been reported as an important predictor variable [41-43]. In the different studies, the sums of skin-folds included not always the same single skin-folds or the same number of skin-folds but consisted mostly of a sum of seven to a maximum of ten skin-folds of both the upper and the lower body.

The sum of skin-folds was related to race performance in runners such as male 10-km runners[41], female [37] and male [22,23,42] marathoners, male ultra-runners such as 100-km ultra-marathoners [38,44], multi-stage ultra-marathoners [25,27], and 24-hour ultra-marathoners [45,46], male triathletes such as Ironman [47,48] and Triple Iron ultra-triathletes [38,49,50]. Additionally, the sum of skin-folds was related to performance in male endurance athletes such as long-distance inline skaters[39] and ultra-endurance mountain bikers [51]. The association of the sum of skin-folds with race performance was also investigated for split disciplines in multi-sports athletes such as triathletes. The sum of skin-folds was related to the split times in male Triple Iron ultra-triathletes [38,50], to the split times in swimming, cycling, running, and overall race time in male Ironman triathletes [52], and to the cycling speed in

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the cycling split in male Ironman triathletes [47]. In Triple Iron ultra-triathletes, the sum of skin-folds was neither associated with the speed in the swim nor in the bike split but showed a significant association with the speed in the run split [49] and overall race time [50]. The sum of skin-folds was not related to race time in male half-marathoners [21], in female Ironman triathletes [33], in male ultra-endurance mountain bikers [53], in male ultra-endurance cyclists [34], and in male open-water ultra-endurance swimmers [54].

Upper and Lower Body Skin-Folds and Their Association with Performance

Differences seemed to exist between single upper and lower body skin-fold thicknesses regarding their association with performance. Arrese and Ostariz showed high correlations between skin-fold thicknesses at the lower limb such as thigh and calf for men in 1,500m and 10,000m running and for women in 400m running [18]. In male Ironman triathletes, the sum of upper body skinfolds and the sum of all skinfolds were related to total race time [47]. The sum of upper body skinfolds and the sum of all skinfolds were also associated with speed in cycling during the race [47].

Taken together, single skin-fold thicknesses seemed to be related to performance in running races for both female and male athletes in rather short distances up to the 100km distance. For longer distances than the 100km ultra-marathon, only male athletes have been investigated and single skin-fold thicknesses showed no relationship to race performance. There seemed also to exist a difference between women and men for the relationship between single skin-fold thicknesses and race performance. Especially for Ironman triathletes, skin-fold thicknesses were related to performance in male, but not in female athletes.

Circumferences of Limbs

A further anthropometric characteristic related to endurance performance is the circumference of limbs of the upper arm [24,26,36,37,55-57], the thigh [24,37,48,52,55] and the calf [33,37,39,48]. Table 2 summarizes the associations

Table 2: Results of the bi-variate associations between limb circumferences and race performance for female and male endurance and ultra-endurance athletes. The athletes are listed with increasing race distance or race duration

Variable	Upper arm	Thigh	Calf
800m runners		+	
1,500m runners		+	
5,000m runners		+	
10,000m runners	+		
Female marathoners	+	+	+
Male marathoners	–	–	–
Marathon split time in male Ironman triathletes	+	+	
Ultra-marathon split time in male Triple Iron ultra-triathletes	+		
Male long-distance inline skaters	+		+
Male ultra-endurance mountain bikers	+	–	–
Female 100-km ultra-marathoners	+	–	+
Male 100-km ultra-marathoners	+	+	–
Male Ironman triathletes	+	+	+
Female Ironman triathletes	–	–	–
Male multi-stage ultra-marathoners	+	–	–
Male 24-hour ultra-marathoners	–	–	–
Male multi-stage ultra-endurance triathletes	–	–	–
Male Triple Iron ultra-triathletes	–	–	–
Male ultra-endurance indoor swimmers	–	–	–

between circumferences of limbs and performance for female and male endurance and ultra-endurance athletes.

The circumference of upper arm was related to race time in runners such as 10-km runners [55], female marathoners [37], female [56] and male [24,57] 100-km ultra-marathoners, male multi-stage ultra-marathoners [26,36], in cyclists such as male ultra-endurance mountain bikers [51], in male long-distance inline skaters [39], and in triathletes such as male Ironman triathletes [48,58]. In triathletes, the upper arm circumference was also related to performance in the marathon split time in male Ironman triathletes [52] and to the run split time in Triple Iron ultra-triathletes [38,50]. The upper arm circumference was not related to race performance in swimmers such as male indoor ultra-endurance swimmers [59], in runners such as male marathoners [22,23], male 24-hour ultra-marathoners [29], and triathletes such as male multi-stage ultra-endurance triathletes [31], female Ironman triathletes [33,35], and male Triple Iron ultra-triathletes [32,50,60].

At the lower body, the associations of the circumferences of thigh and calf with race performance were investigated. The circumference of thigh was related to performance in runners such as 800m runners [55], 1,500m runners [55], 5,000m runners [55], female marathoners [37], and male 100-km ultra-marathoners [24]. In triathletes, the circumference of the thigh was related to overall race time in male Ironman triathletes [48] and marathon split time in male Ironman triathletes [52]. The thigh circumference was, however, not related to race performance in swimmers such as male indoor ultra-endurance swimmers [59], in cyclists such as male ultra-endurance mountain bikers [51], in runners such as female 100-km ultra-marathoners [56], male marathoners [21,22], male multi-stage ultra-marathoners [25-27,36], male 24-hour ultra-marathoners [29], and in multi sports athletes such as male multi-stage ultra-endurance triathletes [31], male Triple Iron ultra-triathletes [32,50,60], and female Ironman triathletes [33,61]. The circumference of calf was related to race time in runners such as female marathoners [37], female 100-km ultra-marathoners [33], male long-distance inline skaters [39], and male Ironman triathletes [48]. In a variety of disciplines and distances, no association between calf circumference and race performance was reported. These were swimmers such as male indoor ultra-endurance swimmers [59], runners such as male marathoners [22,23], ultra-marathoners such as male 100-km ultra-marathoners [24], male 24-hour ultra-marathoners [29], male multi-stage ultra-marathoners [25-27,36], cyclists such as male ultra-endurance mountain bikers [51], and triathletes such as female Ironman triathletes [33,61], male multi-stage ultra-endurance triathletes [31], and male Triple Iron ultra-triathletes [32,50,60].

In summary, the circumferences of limbs were mainly related to performances of rather short duration as has already been found for skin-fold thicknesses. For example, limb circumferences were related to Ironman performance, but not to Triple Iron ultra-triathlon performance for men. There seemed also to exist a sex difference. Especially for Ironman triathletes and marathoners, limb circumferences were related to performance in male, but not in female athletes as has already been found for single skin-fold thicknesses.

Length of Limbs

Also the length of limbs has been reported as an important predictor variable for endurance performance. Table 3 presents the associations between lengths of limbs and performance for female and male endurance and ultra-endurance athletes. The length of the arm was related to race time in male open-water ultra-endurance swimmers [62], but not in male indoor [59] and male open-water [54] ultra-endurance swimmers. Again, no association was found for triathletes such as male multi-stage ultra-endurance triathletes [31], in male Ironman triathletes [48], male Triple Iron ultra-triathletes [50], and female Ironman triathletes [33,61]. The length of the leg was associated with race time in female long-distance inline skaters [63], but not in swimmer such as male indoor [59] and male open-water [54] ultra-endurance swimmers, in runners such as in female 100-km ultra-marathoners [33], male 24-hour ultra-marathoners [29,46], male multi-stage ultra-marathoners [36], and in triathletes such as female [33,61] and male Ironman triathletes[48], male multi-stage ultra-endurance triathletes [31], and male Triple Iron ultra-

Table 3: Results of the bi-variate associations between limb lengths and race performance for female and male endurance and ultra-endurance athletes. The athletes are listed with increasing race distance or race duration

Variable	Arm	Leg
Female 100-km ultra-marathoners		−
Male 100-km ultra-marathoners		
Male multi-stage ultra-marathoners		−
Male 24-hour ultra-marathoners	−	
Female long-distance inline skaters		+
Male Ironman triathletes	−	−
Female Ironman triathletes		−
Male multi-stage ultra-endurance triathletes	−	−
Male Triple Iron ultra-triathletes	−	−
Male indoor ultra-endurance swimmers	−	−
Male open-water ultra-endurance swimmers	+/−	−

triathletes [50].

Body mass, Body Height and Body Mass Index

Body mass is an easy-to-determine variable for anthropometry. In addition to body mass, body height is also an easy-to-determine variable for anthropometry. With the determination of body mass and body height, the variable body mass index using the equation body mass (kg) divided by body height (m^2) can be calculated. Table 4 shows the associations between body mass, body height and body mass index with performance for female and male endurance and ultra-endurance athletes.

Body mass

Body mass was related to race performance in a variety of athletes such as 3,000m steeplechase runners [64], female half-marathoners [19,20], female marathoners [37,65], female [33] and male [57,66] 100-km ultra-marathoners, male 24-hour ultra-marathoners [45,46], male multi-stage ultra-marathoners [26,36], male long-distance inline skaters [39], road cyclists [67], and male off-road cross-country cyclists [68-70]. In triathletes, body mass was related to overall race time in male Ironman triathletes [48,52] and performance in the marathon split in male Ironman triathletes [52]. Body mass was not related to race performance in swimmers such as male indoor [59] and male open-water [54] ultra-endurance swimmers, cyclists such as male ultra-endurance mountain bikers [51,53] and male ultra-endurance road cyclists [71], runners such as male 24-hour ultra-marathoners [29], and triathletes such as female Ironman triathletes [33,61], male multi-stage ultra-endurance triathletes [31], and male Triple Iron ultra-triathletes [32,50,60]. Different findings were reported for body mass in male marathoners where Hagan et al [42] found an association but other studies [22,23] found no association with race times.

Body height

An association between body height and endurance performance has mainly been reported for swimmers [62,72-74]. Body height was related to performance in female and male pool swimmers [72-74] and in male open-water ultra-endurance swimmers [62]. Body height was also related to race performance in road cyclists [67], in female long-distance inline skaters [63], and in female 100-km ultra-marathoners [56]. However, a variety of disciplines showed no association between body height and race performance. These were swimmers such as male indoor ultra-endurance swimmers [59], cyclists such as male ultra-endurance mountain bikers [51] and male ultra-endurance cyclists [71], runners such as male marathoners [22,,23], male 24-hour ultra-marathoners [29,46], male multi-stage ultra-marathoners [25-27,36], triathletes such as male multi-stage ultra-endurance triathletes [31], male Ironman

Table 4: The results of the bi-variate associations between limb circumferences and race performance for female and male endurance and ultra-endurance athletes (The athletes are listed with increasing race distance or race duration)

Variable	Body mass	Body height	Body mass index
3,000m steeple chase runners	+		
Female half-marathoners	+		+
Female marathoners	+		+
Male marathoners	+/–	–	–
Marathon split time in male Ironman triathletes	+		+
Female 100-km ultra-marathoners	+	+	–
Male 100-km ultra-marathoners	+		+
Female 161-km ultra-marathoners			+
Male 161-km ultra-marathoners			+
Male multi-stage ultra-marathoners	+	–	–
Male 24-hour ultra-marathoners	+/–	–	–
Male Ironman triathletes	+	–	+
Female Ironman triathletes	–	–	–
Male long-distance road cyclists	+/–	+/–	–
Male off-road cross country cyclists	+/–		
Male ultra-endurance mountain bikers		–	+
Female ultra-endurance indoor swimmers		+	
Male ultra-endurance indoor swimmers	–	+/–	–
Male open-water ultra-endurance swimmers	–	+	+/–
Female long-distance inline skaters		+	
Male long-distance inline skaters	+		+
Male multi-stage ultra-endurance triathletes	–	–	–
Male Triple Iron ultra-triathletes	–	–	–

triathletes [48], male Triple Iron ultra-triathletes [50,60] and female Ironman triathletes [33,61].

Body mass index

Body mass index was related to performance in runners such as female half-marathoners [19,20], female marathoners [37,65], male 100-km ultra-marathoners [44,57,66], female and male 161-km ultra-marathoners [75], male long-distance inline skaters [39], male ultra-endurance mountain bikers [51], and male open-water ultra-endurance swimmers [62]. In triathletes, body mass index was related to overall race time [48,52] and to the split time in running [52] in male Ironman triathletes. However, body mass index was not related to race performance in different athletes such as male indoor [59] and male open-water [54] ultra-endurance swimmers, in runners such as male marathoners [22,23], female 100-km ultra-marathoners [56], male multi-stage ultra-marathoners [25-27,36], male 24-hour ultra-marathoners [29,46], and in triathletes such as female Ironman triathletes [33,61], male multi-stage ultra-endurance triathletes [31], male ultra-endurance cyclists [71], and male Triple Iron ultra-triathletes [32,50,60].

In summary, the variables body mass, body height and body mass index were mainly related to performances of rather short duration as has already been found for skin-fold thicknesses and limb circumferences. For single sports disciplines such as running, body mass and body mass index seemed an important predictor variable, but not for multi-sports disciplines such as triathlon. This might be due to the fact that body mass and body mass index were rather seldom related to performance in swimmers and cyclists, where swimming and cycling are split disciplines in a triathlon.

Body Fat

Body fat has been reported as an important predictor variable for a variety of disciplines and race distances [9,19,20,22,23.25-27,29,31-34,36-39,40,44-48,50-54,56,58,59-61,65,66,76-81].

When single skin-fold thicknesses are determined, body fat percentage can be calculated using anthropometric equations [82-85].

Body fat was related to race performance in runners such as female half-marathoners [19,20], in female [37,65] and male [22,23] marathoners, in ultra-marathoners such as male 100-km [38,44,57,66], 161-km [77], and 24-hour [45,46] ultra-marathoners, in swimmers such as female pool swimmers [78], in male long-distance inline skaters [39], in male ultra-endurance mountain bikers [51], in male ultra-endurance cyclists [35,71], and in triathletes such as male Ironman triathletes [35,40,47,48,52,58,79,80,81] and male Triple Iron ultra-triathletes [58]. Additionally, body fat was related to the run split time in Triple Iron ultra-triathletes [38,50] and to cycling speed in the cycling split in Ironman triathletes [47].

However, body fat was not related to race performance in ultra-endurance swimmers such as male indoor [59] and male open-water [54] ultra-endurance swimmers, in ultra-runners such as male multi-stage ultra-marathoners [25-27,36], male 24-hour ultra-marathoners [29], female 100-km [56] and female 161-km [9] ultra-marathoners, ultra-endurance cyclists such as male mountain bikers [53], in male ultra-endurance cyclists [34], and triathletes such as female Ironman triathletes [33,61,81], male multi-stage ultra-endurance triathletes [31] and in male Triple Iron ultra-triathletes [32,50,60].

Considering these findings, disparate results have been reported for the association between calf skin-fold thickness and performance in male half-marathoners (Table 1), the arm length in male open-water ultra-endurance swimmers (Table 3), body mass in male marathoners, in male long-distance road cyclists, in male off-road cross country cyclists, body height in male long-distance road cyclists and male ultra-endurance indoor swimmers and body mass index in male open-water ultra-endurance swimmers (Table 4). These disparate findings might be explained by different performance levels of the athletes and different numbers of included subjects.

TRAINING CHARACTERISTICS

Apart from selected anthropometric characteristics, training variables such as speed during training and volume have also been reported to be related to endurance performance [86-92].

Training Volume

Volume in training can be expressed as completed kilometers or completed hours. Training volume expressed in kilometers or hours per time period seemed to be an important predictor variable for different sports disciplines and race distances [65,93-96]. The weekly training hours were related to race time in triathletes such as female Ironman triathletes [80,81], male Triple Iron ultra-triathletes [58] and in male 100-km ultra-marathoners [38,44,57,97]. Weekly training hours were, however, not associated with race performance in runners such as male half-marathoners [21], male marathoners [22,23], female [56] and male [97] 100-km ultra-marathoners, male multi-stage ultra-marathoners [27,28], male 24-hour ultra-marathoners [29,30,45], and in triathletes such as female [61] and male [81] Ironman triathletes, and male Triple Iron ultra-triathletes [49,50].

The association of volume in cycling training with race performance was investigated for different cycling disciplines. In ultra-endurance cyclists, the completed cycling distance per training unit and the duration per training unit were related to race time [71,98]. The annually completed cycling kilometers were related to race time in male ultra-endurance mountain bikers [51,53]. The weekly completed running kilometers were related to race time in male half-marathoners [21], in female marathoners [65], in male 100-km ultra-marathoners [38,44,57,66,97], in male Triple Iron ultra-triathletes [58], to race performance in male 24-hour ultra-marathoners [45,46], but not in in male multi-stage

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ultra-marathoners [27] and female 100-km ultra-marathoners [56].

Additionally, the association between the single training units and race performance was investigated. The duration per training unit was related to race time in male [39,99] and female long-distance inline skaters [100] and in female marathoners [65]. The distance per training unit was associated with race time in male ultra-endurance mountain bikers [51] and in marathon runners [42,101]. The mean duration and the mean distance per training unit were related to race time in male ultra-endurance cyclists [71] and in female marathoners [65]. The number of weekly training units was related to race time in female long-distance inline skaters [63], in male half-marathoners [21], and in male [22] and female marathoners [65,93].

In triathletes, the training volume of the single disciplines was recorded and related to performance in the split disciplines. In male Ironman triathletes, the weekly swim kilometers [40,48] and the weekly swim hours [48] were related to the split time in swimming during the Ironman. Weekly swim hours and weekly swim kilometers were, however, not related to swim split time in female Ironman triathletes [61]. In the cycling split, both the weekly cycling kilometers and weekly cycling hours were related to Ironman race time in female [61] and male [48] Ironman triathletes. The weekly cycling kilometers were related to overall race time in male Triple Iron ultra-triathletes [58].

Speed during Training

Training pace seemed to be an important predictor variable for different sports disciplines [65,102,103]. Peak running velocity was highly predictive of distance running performance in highly-trained endurance runners [104,105]. Peak treadmill running velocity has been shown a good predictor of running performance for both marathoners and ultra-marathoners [89] and short-distance triathletes [102,106]. Swimming speed was related to race time in in male and female open-water ultra-endurance swimmers [62] and swimming split time in male Ironman triathletes [48]. Cycling speed during training was related to overall race time in male [58] but not in female [61] Ironman triathletes. Speed in cycling was related to overall race time in male ultra-endurance road cyclists [98] and male ultra-endurance mountain bikers [51,53], and to the bike split time in an Ironman triathlon [35,40]. Running speed during training was related to race time in female [19,20] and male [21,103] half-marathoners, in female [37] and male [22,23,40] marathoners, in male 100-km ultra-marathoners [44,57,66], and in male multi-stage ultra-marathoners [28]. In triathletes, running speed during training was related to marathon split time [48] and overall race time [107] in male Ironman triathletes.

However, running speed during training was not related to race performance in male 24-hour runners [45,46], and in female Ironman triathletes [61]. In male long-distance inline skaters, skating speed during training was related to race time [39]. No association with training variables was reported for male Triple Iron ultra-triathletes [50] and male multi-stage ultra-marathoners [27].

Interaction between Anthropometric and Training Characteristics

The question arises now whether anthropometric or training characteristics were more important to predict endurance performance. Several studies investigated the interaction between anthropometric and training characteristics using multi-variate correlation analyses [21,22,93,100,108,109] since anthropometry and training were bi-variately related [21,22,24,30,45,110].

An association between physical training and body fat has been reported. It is important to know that training leads to a reduction of both skin-fold thicknesses [111] and body fat percentage [112]. The loss of body appears to be specific to the muscular groups used during training [111]. The thickness of skin-folds seems to decrease with increasing running distance. Legaz Arrese et al. [113] found lower skin-fold thicknesses in marathoners compared to runners competing in shorter running distances. Athletes with lower body fat are lighter and therefore able to run faster. However, the correlation between skin-fold thickness and body fat with running speed does not prove cause and effect. Athletes with low body fat might also have reduced their body fat by diet [114,115].

The prevalence of eating disorders is higher in athletes than in controls, higher in women than in men, and more common among those competing in leanness-dependent and weight-dependent sports than in other sports [116,117].

For runners, it has been shown that lower body fat [20,22,24,45,110] and lower skin-fold thicknesses [19,20,24,45,110] were associated with a faster running speed in training. Additionally, training volume expressed in weekly running kilometers was associated with thickness of skinfolds [24,45,110] and percent body fat [24,45,110]. The circumference of upper arm was related to weekly running kilometers [110] and running speed during training [110] in 100-km ultra-marathoners. In female half-marathoners, running speed during training was related to mid-axilla, subscapular, abdominal, and suprailiacal skin-fold thickness, the sum of eight skin-fold thicknesses and percent body fat [19].

Most probably athletes such as distance runners profit from thinness to achieve fast race times. A recent study investigated the association between anthropometric and training characteristics with race performance for half-marathoners, marathoners and ultra-marathoners [100]. Body fat was related to half-marathon, marathon, and ultra-marathon race times. In half-marathoners and marathoners, speed during training was related to race times. In ultra-marathoners, however, weekly running kilometers were related to running times. This study showed that body fat and training characteristics were associated with running times in half-marathoners, marathoners, and ultra-marathoners.

The distance of the intended race seemed to influence the training behavior in endurance and ultra-endurance athletes [58,66]. Marathoners seemed rather to rely on a high running speed during training whereas ultra-marathoners seemed to rely on a high running volume during training [66]. Marathoners completed significantly fewer hours and significantly fewer kilometers during the training week, but they were running significantly faster during training than ultra-marathoners [66]. Similar findings were reported for the comparison for Ironman triathletes competing for 3.8 km swimming, 180 km cycling and 42.195 km running and Triple Iron ultra-triathletes competing for 11.4 km swimming, 540 km cycling and 126.6 km running [58]. Triple Iron ultra-triathletes relied more on training volume in cycling and running, whereas speed in cycling training was related to race time in Ironman triathletes [58].

A variety of studies showed that both anthropometric and training characteristics predicted performance when anthropometric and training variables were multi-variately associated with performance [21,22,80,109,114]. In male marathoners, both a low body fat and a fast running speed during training were the best predictor variables [22]. Speed during training was of higher relevance since percent body fat explained only 4% of the variance [22]. Low body fat alone might not be sufficient to achieve a fast marathon time [22]. In male half-marathoners, body mass index and running speed during training were the best predictors [21]. In male ultra-endurance cyclists, anthropometry showed a moderate association with speed in the race, whereas training volume showed no association [109]. In female short-distance triathletes, training parameters were more important than anthropometric measures in the prediction of performance [114]. In female and male Ironman triathletes, however, percent body fat was not related to training volume [80].

THE ASPECT OF RACE DISTANCE AND SPECIFIC PRE-RACE PREPARATION

The different preparations for the different race distances seems to have an effect on both the training and the anthropometry of the athletes [38,40]. Athletes competing in and preparing for shorter distances seemed thinner than athletes competing in and preparing for ultra-distances [23,38,66,118]. Athletes seemed also to adapt their training regarding the intended race distance. Training distances appeared to be more important than training paces in the preparation for an ultra-endurance triathlon such as an Ironman triathlon [119]. The comparison of male half-marathoners and marathoners showed that half-marathoners were heavier, had longer legs, thicker upper arms, a thicker thigh, a higher sum of skinfold thicknesses, a higher body fat percentage and a higher skeletal muscle mass than marathoners [118]. Half-marathoners had fewer years of experience, completed fewer weekly training kilometers, and fewer weekly running hours than the marathoners. Predictor variables for race time were different between half-marathoners and marathoners. Body mass index, percent body fat and speed in running during training were related to race time in half-marathoners. For marathoners, percent body fat and speed in running during training were associated with race time [118]. When anthropometric characteristics were compared between marathoners and 100-km ultra-marathoners, marathoners had a significantly lower calf circumference and a significantly thicker skinfold at pectoral, axilla, and suprailiacal sites compared to ultra-marathoners [66]. When marathoners and 24-hour ultra-marathoners were compared, the 24-hour ultra-marathoners had a lower limb circumference at upper arm and thigh, and a lower skinfold thickness at the pectoral, axilla, and suprailiacal site compared to the marathoners [23]. During training, the 24-hour ultra-marathoners completed more weekly running hours and achieved more running kilometers, however, they were running slower compared with the marathoners [23].

Anthropometric and training characteristics were differently related to performance regarding the length of a race. In 24-hour ultra-marathoners, neither anthropometric nor training variables were associated with achieved race kilometers. In marathoners, however, percent body fat and running speed during training were related to marathon race times [23]. However, the comparison of 100-km ultra-marathoners and Triple Iron ultra-triathletes showed that ultra-triathletes had higher body mass, shorter legs, a higher circumference of upper arm and thigh, a lower sum of skin-folds, and lower percent body fat compared to runners [38]. Weekly training volume was higher for triathletes, and weekly hours in running and weekly kilometers in running were higher for runners. Similar findings were reported for the comparison between Ironman triathletes and Triple Iron ultra-triathletes [58]. The Triple Iron ultra-triathletes were smaller, had shorter limbs, a higher body mass index, and larger limb circumferences than the Ironman triathletes. The Triple Iron ultra-triathletes trained for more hours and covered more kilometers, but speed in running during training was slower compared with the Ironman triathletes [58]. When ultra-endurance cyclists preparing for ‘Paris-Brest-Paris’ where compared with ultra-endurance cyclists preparing for the ‘Race Across America’, the qualifiers in the longer race had greater intensity in training while the qualifiers in the shorter race relied more on training volume [120]. The comparison of finishers and non-finishers in an ultra-cycling race such as the 'Swiss Cycling Marathon' covering 720 km showed that the finishers had a lower body mass, a lower body mass index, a lower circumference of upper arm and thigh, a lower percentage of body fat, completed more weekly training units, covered more kilometers in the longest training ride, rode at a faster speed during training, rode more kilometers per week and for more hours, and had more previous finishes in the 'Swiss Cycling Marathon' compared to the non-finishers [98].

DIFFERENCES IN ANTHROPOMETRIC AND TRAINING CHARACTERISTICS BETWEEN WOMEN AND MEN

Several studies compared anthropometric and training characteristics between female and male endurance athletes [77,121,122]. Regarding anthropometry, women are smaller than men, have more body fat and a lower skeletal muscle mass [77,123]. These differences lead to differences in the predictor variables [62,124,125]. In a 12-min run, women and men achieved different performances [123]. The average sex difference in 12-min run performance is primarily due to differences in percent fat and cardiorespiratory capacity [123].

When female and male half-marathoners were compared, two skin-fold thicknesses (*i.e.* abdominal and calf) were significantly and positively correlated with race time in men whereas in women, five (*i.e.* pectoral, mid-axilla, subscapular, abdominal, and suprailiacal) showed positive and significant relations with total race time [124]. In men, mean weekly running distance, minimum distance run per week, maximum distance run per week, mean weekly hours of running, number of running training sessions per week, and mean speed of the training sessions were significantly and negatively related to total race time, but not in women [124]. Interaction analyses suggested that race time was more strongly associated with anthropometry in women than men. Race time for women was independently associated with the sum of eight skin-folds; but for men, only the mean speed during training sessions was independently associated. Skin-fold thicknesses and training variables in these groups were differently related to race time according to their sex. The comparison of female and male open-water ultra-endurance swimmers showed that body height, body mass index, length of arm, and swim speed during training were related to race time in men [62]. For women, swimming speed during training was associated with race time [62]. In the multivariate analysis for the men, body mass index and swimming speed during training were related to race time [62]. When female and male Ironman triathletes were compared, low skinfold thicknesses of the upper body were related to race performance in male, but not in female Ironman triathletes [47]. Percent body fat showed a relationship to total race time in male triathletes, and training volume showed an association with total race time in female triathletes [80,81]. The comparison of female and male 161-km ultra-marathoners showed that a significant positive correlation between percent body fat and finish time for men but not for women, and percent body fat values were lower for finishers than non-finishers for men and women [77]. In pool swimmers, measurements of body composition and somatotype were predictors of swimming performance in women but not in men [121].

THE ASPECT OF PREVIOUS EXPERIENCE

Previous experience seems to be a very important predictor variable for endurance performance [126-128]. Several studies corrected the association of anthropometric and training characteristics with performance with the aspect of pre-race experience in multi-variate regression analyses [45,48,50,51,61,97,107].

For ultra-distances, personal best times in shorter races were important predictor variables [45,107,126,127,129]. For ultra-runners, personal best marathon time seemed a strong predictor variable. Personal best marathon time was related to performance in male 24-hour ultra-marathoners [29,45,46], in male [44,57,97] and female [56] 100-km ultra-marathoners, in male [107] and female [33] Ironman triathletes, but not in in male multi-stage ultra-marathoners [27]. For Ironman triathletes, both the personal best marathon time and the personal best time in an Olympic distance triathlon were strong predictor variables in both women and men [48,61,107,127]. Personal best time in an Olympic distance triathlon was related to Ironman race time in male [48,107] and female [33,61] Ironman triathletes. These variables were able to predict Ironman race time. Speed in running training, the personal best marathon time and the personal best time in an Olympic distance triathlon explained 64% of the variance in an Ironman triathlon for male triathletes [107]. For female Ironman triathletes, personal best marathon time and personal best time in an Olympic distance triathlon explained 53% of the variance of Ironman race time [61]. In a further study, the previous best performances in an Olympic distance triathlon coupled with the weekly cycling distances and the longest training ride could partially predict overall performance [127].

Also for longer triathlon distances than the Ironman triathlon, the personal best time in a shorter race was an important predictor variable for an ultra-triathlon. Personal best time in an Ironman triathlon was related to race time in a Triple Iron ultra-triathlon [50]. In male Deca Iron ultra-triathletes covering 38 km swimming, 1,800 km cycling and 422 km running, race time was related to both the number of finished Triple Iron ultra-triathlons (*i.e.* 11.4 km swimming, 540 km cycling, and 126.6 km running) and the personal best time in a Triple Iron ultra-triathlon [129]. In male Triple Iron ultra-triathletes, however, personal best Ironman time was not related to race time but personal best time in Triple Iron ultra-triathlon [50].

The previous personal best time in the same race distance was an important predictor variable for race time. This personal best time was related to race time in male long-distance inline skaters [99], in male ultra-endurance mountain bikers [51], male 100-km ultra-marathoners [57], male Triple Iron ultra-triathletes [50], female and male Ironman triathletes [33,81], and male 24-hour ultra-marathoners [29]. In 24-hour ultra-marathoners, the personal best marathon time, the personal best time in a 100-km ultra-marathon and the best performance in a 24-hour ultra-marathon were the best predictor variables [45]. In another study, the personal best marathon time and the longest training run prior to the race were the best predictors [46].

For some race distances, the number of previously completed races was an important predictor variable. For female marathoners, the number of previous completed marathons was related to marathon race time [65]. The number of completed 100-km ultra-marathons was associated with race time in male 100-km ultra-marathoners [57]. In male 24-hour ultra-marathoners, the number of finished marathons and the number of finished 24-hour ultra-marathons was not related to race performance [29,45]. In female Ironman triathletes, the number of completed Olympic distance triathlons and the number of complete Ironman triathlons were not associated with race time [33]. In male Triple Iron ultra-triathletes, the number of previously completed Ironman and Triple Iron ultra-triathlons was not associated with race time [50].

Anthropometric and training characteristics seemed to be of low importance regarding ultra-endurance performance when corrected with aspects of previous experience[33,48,51]. When anthropometric characteristics, training variables and previous experience were multi-variately associated with Ironman race time in male athletes, personal best marathon time and personal best time in an Olympic distance triathlon were the best predictor variables [48]. In long-distance mountain bikers competing in the 'Swiss Bike Masters', personal best time in the 'Swiss Bike Masters', annual total cycling kilometers and annual road cycling kilometers were the best predictor variables [51].

In the aspect of previous experience as an athlete, also the number of years training and competing was correlated to race performance. The number of years training was related to marathon race time in female marathoners [93] and to 10 km race time in male runners [41]. Years as active athlete were not related to performance in male multi-stage ultra-marathoners [28], in male open-water ultra-endurance swimmers [54], in male 24-hour ultra-marathoners [45,46], in male 100-km ultra-marathoners[97], in male ultra-endurance mountain bikers [51], and in male ultra-endurance cyclists [71].

PHYSIOLOGICAL CHARACTERISTICS

Apart from anthropometric characteristics, training variables and previous experience, also physiological characteristics predict endurance performance [130,131]. Several laboratory and field studies showed that physiological characteristics such as maximum oxygen uptake (VO_2max) [42,96,108,128,132-141], anaerobic threshold [64], lactate threshold [129,140,141], lactate threshold velocity [142,143], VO_2 at lactate threshold [143], ventilatory threshold [136], and velocity at VO_2max (vVO_2max) [144] were related to performance. In off-road cross-country cyclists, VO_2max was a strong predictor variable for performance [69,70]. Among well-trained female and male runners heterogeneous in VO_2max and running performance, VO_2max was the best predictor of running performance [144]. Final treadmill velocity in a VO_2max test is the single best predictor of 5000-m performance in untrained and trained states [143]. In top-class marathoners, marathon performance time was inversely correlated with VO_2max and predicted 59% of the variance of marathon performance time.

CONCLUSION

To summarize, although several studies showed strong bi-variate correlations between single anthropometric and training characteristics, previous experience such as personal best time in a shorter race seems the better predictor for endurance and ultra-endurance athletes than a thin body and a high speed during training. Ultra-endurance athletes seemed to prepare differently for their races compared to endurance athletes. The different length of the races seemed also to have an influence on pre-race body composition. The most important predictor variables for ultra-endurance athletes were a fast personal best time in shorter races, a low body fat and a high speed during training units.

REFERENCES

[1] Zaryski C, Smith DJ. Training principles and issues for ultra-endurance athletes. *Curr Sports Med Rep* 2005;4:165-70.

[2] Eichenberger E, Knechtle B, Christoph AR, et al. No gender difference in peak performance in ultra-endurance swimming performance - analysis of the 'Zurich 12-h Swim' from 1996 to 2010. *Chin J Physiol* 2012;55:346-51.

[3] Eichenberger E, Knechtle B, Knechtle P, et al. Best performances by men and women open-water swimmers during the 'English Channel Swim' from 1900 to 2010. *J Sports Sci* 2012;30:1295-301.

[4] Eichenberger E, Knechtle B, Knechtle P, et al. Sex difference in open-water ultra-swim performance in the longest freshwater lake swim in Europe: Sex difference in ultra-swimming. *J Strength Cond Res* 2013;27:1362-9.

[5] Fischer G, Knechtle B, Rüst CA, Rosemann T. Male swimmers cross the English Channel faster than female swimmers. *Scand J Med Sci Sports* 2013;23:e48-55.

[6] Rüst CA, Knechtle B, Rosemann T, Lepers R. Men cross America faster than women - the 'Race Across America' (RAAM) from 1982 to 2012. *Int J Sports Physiol Perform* 2013;8:611-7.

[7] Abou Shoak M, Knechtle B, Knechtle P, et al. Participation and performance trends in ultra-cycling. *Open Access J Sports Med* 2013; 4:41-51.

[8] Zingg M, Knechtle B, Rüst CA, et al. Age and gender difference in non-drafting ultra-endurance cycling performance – the 'Swiss Cycling Marathon'. *Extrem Physiol Med* 2013;2:18.

[9] Hoffman MD. Performance trends in 161-km ultramarathons. *Int J Sports Med* 2010;31:31-7.

[10] Rosemann T, Lepers R, Knechtle B, et al. Master runners dominate the 24-hour ultra-marathons worldwide – a retrospective data analysis from 1998 to 2011. *Extrem Physiol Med* 2013;2:21.

[11] Zingg M, Rüst CA, Knechtle B, et al. Analysis of participation and performance in athletes by age group in ultra-marathons of more than 200 km in length. *Int J Gen Med* 2013:6 209-20

[12] Da Fonseca-Engelhardt K, Knechtle B, Rüst CA, et al. Participation and performance trends in ultra-endurance running races under extreme conditions - 'Spartathlon' versus 'Badwater'. *Extreme Physiology and Medicine* 2013 May 1;2(1):15.

[13] Rüst CA, Knechtle B, Rosemann T, Lepers R. Analysis of performance and age of the fastest 100-miles ultra-marathoners worldwide. *Clinics* 2013;68:605-11.

[14] Knoth C, Knechtle B, Rüst CA, et al. Participation and performance trends in multi-stage ultra-marathons - The 'Marathon des Sables' from 2003 – 2012. *Extrem Physiol Med* 2012;1:13.

[15] Eichenberger E, Knechtle B, Rüst CA, et al. Age and gender interactions in mountain ultra-marathon running – the 'Swiss Alpine Marathon'. *Open Access J Sports Med* 2012;3:73-80.

[16] Rüst CA, Knechtle B, Knechtle P, et al. Gender difference and age-related changes in performance at the long distance duathlon World Championships. *J Strength Cond Res* 2013;27:293-301.

[17] Knechtle B, Knechtle P, Lepers R. Participation and performance trends in ultra-triathlons from 1985 to 2009. *Scand J Med Sci Sports* 2011;21:e82-90.

[18] Arrese AL, Ostáriz ES. Skinfold thicknesses associated with distance running performance in highly trained runners. *J Sports Sci* 2006;24:69-76.

[19] Knechtle B, Knechtle P, Barandun U, Rosemann T. Anthropometric and training variables related to half-marathon running performance in recreational female runners. *Phys Sportsmed*. 2011;39:158-66.

[20] Knechtle B, Knechtle P, Barandun U, et al. Predictor variables for half marathon race time in recreational female runners. *Clinics (Sao Paulo)* 2011;66:287-91.

[21] Rüst CA, Knechtle B, Knechtle P, et al. Predictor variables for a half marathon race time in recreational male runners. *Open Access J Sports Med* 2011;2:113-119.

[22] Barandun U, Knechtle B, Knechtle P, et al. Running speed during training and percent body fat predict race time in recreational male marathoners. *Open Access J Sports Med* 2012;3:51-58.

[23] Rüst CA, Knechtle B, Knechtle P, Rosemann T. Comparison of anthropometric and training characteristics between recreational male marathoners and 24-hour ultra-marathoners. *Open Access J Sports Med* 2012;3:121-129.

[24] Knechtle B, Baumgartner S, Knechtle P, et al. Changes in skinfolds and body fat in ultra-marathoners. *Open Access J Sports Med* 2012;3:147-157.

[25] Knechtle B, Knechtle P, Rosemann T. Race performance in male mountain ultra-marathoners: anthropometry or training? *Percept Mot Skills* 2010;110:721-35.

[26] Knechtle B, Duff B, Welzel U, Kohler G. Body mass and circumference of upper arm are associated with race performance in ultraendurance runners in a multistage race--the Isarrun 2006. *Res Q Exerc Sport* 2009;80:262-8.

[27] Knechtle B, Duff B, Schulze I, Rosemann T, Senn O. Anthropometry and pre-race experience of finishers and nonfinishers in a multistage ultra-endurance run--Deutschlandlauf 2007. *Percept Mot Skills* 2009;109:105-18.

[28] Knechtle B, Rosemann T. Skin-fold thickness and race performance in male mountain ultra-marathoners. *J Hum Sports Exerc* 2009;4: 211-20.

[29] Knechtle B, Wirth A, Knechtle P, et al. Personal best marathon performance is associated with performance in a 24-h run and not anthropometry or training volume. *Br J Sports Med* 2009;43:836-9.

[30] Knechtle B, Knechtle P, Rosemann T. No association of skin-fold thickness and training with race performance in male ultra-endurance runners in a 24-hour run. *J Hum Sports Exerc* 2011;6:94-100.

[31] Knechtle B, Knechtle P, Andonie JL, Kohler G. Influence of anthropometry on race performance in extreme endurance triathletes: World Challenge Deca Iron Triathlon 2006. *Br J Sports Med* 2007;41:644-8.

[32] Knechtle B, Kohler G. Running performance, not anthropometric factors, is associated with race success in a Triple Iron Triathlon. *Br J Sports Med* 2009;43:437-41.

[33] Knechtle B, Wirth A, Rosemann T. Is body fat a predictor variable for race performance in recreational female Ironman triathletes? *Medicina Sportiva* 2011;15:6-12.

[34] Knechtle B, Knechtle P, Rosemann T. No correlation of skin-fold thickness and race performance in male ultra-endurance cyclists in a 600 km ultra-cycling marathon. *Human Movement* 2009;10:91-95.

[35] Rüst CA, Knechtle B, Knechtle P, et al. A comparison of anthropometric and training characteristics among recreational male ironman triathletes and ultra-endurance cyclists. *Chin J Physiol* 2012;55:114-24.

[36] Knechtle B, Knechtle P, Schulze I, Kohler G. Upper arm circumference is associated with race performance in ultra-endurance runners. *Br J Sports Med* 2008;42:295-9;

[37] Schmid W, Knechtle B, Knechtle P, et al. Predictor variables for marathon race time in recreational female runners. *Asian J Sports Med* 2012;3:90-8.

[38] Knechtle B, Knechtle P, Rosemann T. Similarity of anthropometric measures for male ultra-triathletes and ultra-runners. *Percept Mot Skills* 2010;111:805-18.

[39] Knechtle B, Knechtle P, Rüst CA, et al. Predictor variables of performance in recreational male long-distance inline skaters. *J Sports Sci* 2011;29:959-66.

[40] Gianoli D, Knechtle B, Knechtle P, et al. Comparison between recreational male ironman triathletes and marathon runners. *Percept Mot Skills* 2012;115:283-99

[41] Bale P, Bradbury D, Colley E. Anthropometric and training variables related to 10km running performance. *Br J Sports Med* 1986;20: 170-3.

[42] Hagan RD, Smith MG, Gettman LR. Marathon performance in relation to maximal aerobic power and training indices. *Med Sci Sports Exerc* 1981;13:185-9.

[43] Legaz-Arrese A, Kinfu H, Munguía-Izquierdo D, et al. Basic physiological measures determine fitness and are associated with running performance in elite young male and female Ethiopian runners. *J Sports Med Phys Fitness* 2009;49:358-63.

[44] Knechtle B, Knechtle P, Rosemann T, Senn O. What is associated with race performance in male 100-km ultra-marathoners--anthropometry, training or marathon best time? *J Sports Sci* 2011;29:571-7.

[45] Knechtle B, Knechtle P, Rüst CA, Rosemann T. Leg skinfold thicknesses and race performance in male 24-hour ultra-marathoners. *Proc (Bayl Univ Med Cent)* 2011;24:110-4.

[46] Knechtle B, Knechtle P, Rosemann T, Lepers R. Personal best marathon time and longest training run, not anthropometry, predict performance in recreational 24-hour ultrarunners. *J Strength Cond Res* 2011;25:2212-8.

[47] Knechtle B, Knechtle P, Rosemann T. Upper body skinfold thickness is related to race performance in male Ironman triathletes. *Int J Sports Med* 2011;32:20-7.

[48] Rüst CA, Knechtle B, Knechtle P, et al. Personal best times in an Olympic distance triathlon and a marathon predict Ironman race time in recreational male triathletes. *Open Access J Sports Med* 2011;2:121-9.

[49] Knechtle B, Knechtle P, Rosemann T. Skin-fold thickness and training volume in ultra-triathletes. *Int J Sports Med* 2009;30:343-7.

[50] Knechtle B, Knechtle P, Rosemann T, Senn O. Personal best time, not anthropometry or training volume, is associated with total race time in a triple iron triathlon. *J Strength Cond Res* 2011;25:1142-50.

[51] Knechtle B, Knechtle P, Rosemann T, Senn O. Personal best time and training volume, not anthropometry, is related to race performance in the 'Swiss Bike Masters' mountain bike ultramarathon. *J Strength Cond Res* 2011;25:1312-7.

[52] Knechtle B, Wirth A, Alexander Rüst C, Rosemann T. The relationship between anthropometry and split performance in recreational male Ironman triathletes. *Asian J Sports Med* 2011;2:23-30.

[53] Knechtle B, Rosemann T. No correlation of skin-fold thickness and race performance in male mountain bike ultra-marathoners. *Medicina Sportiva* 2009;13:146-50.

[54] Knechtle B, Baumann B, Knechtle P, Rosemann T. What influences race performance in male open-water ultra-endurance swimmers: anthropometry or training? *Human Movement* 2000;11:91-5.

[55] Tanaka K, Matsuura Y. A multivariate analysis of the role of certain anthropometric and physiological attributes in distance running. *Ann Hum Biol* 1982;9:473-82.

[56] Knechtle B, Knechtle P, Rosemann T, Lepers R. Predictor variables for 100 km race time in female ultra-marathoners. *Medicina Sportiva* 2010;14:214-220.

[57] Knechtle B, Knechtle P, Rosemann T, Lepers R. Predictor variables for a 100-km race time in male ultra-marathoners. *Percept Mot Skills* 2010;111:681-93.

[58] Knechtle B, Knechtle P, Rüst CA, Rosemann T. A comparison of anthropometric and training characteristics of Ironman triathletes and Triple Iron ultra-triathletes. *J Sports Sci* 2011;29:1373-80.

[59] Knechtle B, Knechtle P, Kohler G. No correlation of anthropometry and race performance in ultra-endurance swimmers at a 12-hours-swim. *Anthropol Anz* 2008;66:73-9.

[60] Knechtle B, Duff B, Amtmann G, Kohler G. Cycling and running performance, not anthropometric factors, are associated with race performance in a Triple Iron Triathlon. *Res Sports Med* 2007;15:257-69.

[61] Rüst CA, Knechtle B, Wirth A, et al. Personal best times in an olympic distance triathlon and a marathon predict an ironman race time for recreational female triathletes. *Chin J Physiol* 2012;55:156-62.

[62] Knechtle B, Baumann B, Knechtle P, Rosemann T. Speed during training and anthropometric measures in relation to race performance by male and female open-water ultra-endurance swimmers. *Percept Mot Skills* 2010;111:463-74.

[63] Knechtle B, Knechtle P, Rosemann T, Lepers R. Is body fat a predictor of race time in female long-distance inline skaters? *Asian J Sports Med* 2010;1:131-6.

[64] Kenney WL, Hodgson JL. Variables predictive of performance in elite middle-distance runners. *Br J Sports Med* 1985;19:207-9.

[65] Hagan RD, Upton SJ, Duncan JJ, Gettman LR. Marathon performance in relation to maximal aerobic power and training indices in female distance runners. *Br J Sports Med* 1987;21:3-7.

[66] Rüst CA, Knechtle B, Knechtle P, Rosemann T. Similarities and differences in anthropometry and training between recreational male 100-km ultra-marathoners and marathoners. *J Sports Sci* 2012;30:1249-57.

[67] Swain DP. The influence of body mass in endurance bicycling. *Med Sci Sports Exerc* 1994;26:58-63.

[68] Gregory J, Johns DP, Walls JT. Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. *J Strength Cond Res* 2007;21:17-22.

[69] Impellizzeri FM, Marcora SM, Rampinini E, et a. Correlations between physiological variables and performance in high level cross country off road cyclists. *Br J Sports Med* 2005;39:747-51.

[70] Impellizzeri FM, Rampinini E, Sassi A, et al. Physiological correlates to off-road cycling performance. *J Sports Sci*. 2005;23:41-7.

[71] Knechtle B, Wirth A, Knechtle P, et al. No improvement in race performance by naps in male ultra-endurance cyclists in a 600-km ultra-cycling race. *Chin J Physiol* 2012;55:125-33.

[72] Chengalur SN, Brown PL. An analysis of male and female Olympic swimmers in the 200-meter events. *Can J Sport Sci* 1992;17:104-9.

[73] Jagomägi G, Jürimäe T. The influence of anthropometrical and flexibility parameters on the results of breaststroke swimming. *Anthropol Anz* 2005;63:213-9.

[74] Zampagni ML, Casino D, Benelli P, et al. Anthropometric and strength variables to predict freestyle performance times in elite master swimmers. *J Strength Cond Res* 2008;22:1298-307.

[75] Hoffman MD. Anthropometric characteristics of ultramarathoners. *Int J Sports Med* 2008;29:808-11.

[76] Landers GJ, Blanksby BA, Ackland TR, Smith D. Morphology and performance of world championship triathletes. *Ann Hum Biol* 2000;27:387-400.

[77] Hoffman MD, Lebus DK, Ganong AC, et al. Body composition of 161-km ultramarathoners. *Int J Sports Med* 2010;31:106-9.

[78] Tuuri G, Loftin M, Oescher J. Association of swim distance and age with body composition in adult female swimmers. *Med Sci Sports Exerc* 2002;34:2110-4.

[79] Bernheim AM, Attenhofer Jost CH, Knechtle B, et al. The right ventricle best predicts the race performance in amateur Ironman athletes. *Med Sci Sports Exerc* 2013;45:1593-9.

[80] Knechtle B, Wirth A, Baumann B, et al. Differential correlations between anthropometry, training volume, and performance in male and female Ironman triathletes. *J Strength Cond Res* 2010;24:2785-93.

[81] Knechtle B, Wirth A, Baumann B, et al. Personal best time, percent body fat, and training are differently associated with race time for male and female ironman triathletes. *Res Q Exerc Sport* 2010;81:62-8.

[82] Ball SD, Altena TS, Swan PD. Comparison of anthropometry to DXA: a new prediction equation for men. *Eur J Clin Nutr* 2004;58: 1525-31.

[83] Brodie D, Moscrip V, Hutcheon R. Body composition measurement: A review of hydrodensitometry, anthropometry, and impedance methods. *Nutr* 1998;14:296-310.

[84] Knechtle B, Wirth A, Knechtle P, et al. A comparison of fat mass and skeletal muscle mass estimation in male ultra-endurance athletes using bioelectrical impedance analysis and different anthropometric methods. *Nutr Hosp* 2011;26:1420-7.

[85] Ostojic SM. Estimation of body fat in athletes: skinfolds vs bioelectrical impedance. *J Sports Med Phys Fitness* 2006;46:442-6.

[86] Millet GP, Candau RB, Barbier B, et al. Modeling the transfers of training effects on performance in elite triathletes. *Int J Sports Med* 2002;23:55-63.

[87] Garcin M, Fleury A, Ansart N, et al. Training content and potential impact on performance: a comparison of young male and female endurance-trained runners. *Res Q Exerc Sport* 2006;77:351-61.

[88] Esteve-Lanao J, San Juan AF, Earnest CP, et al. How do endurance runners actually train? Relationship with competition performance. *Med Sci Sports Exerc* 2005;37:496-504.

[89] Noakes TD, Myburgh KH, Schall R. Peak treadmill running velocity during the VO2 max test predicts running performance. *J Sports Sci* 1990;8:35-45.

[90] Hewson DJ, Hopkins WG. Specificity of training and its relation to the performance of distance runners. *Int J Sports Med* 1996;17: 199-204.

[91] Hewson DJ, Hopkins WG. Prescribed and self-reported seasonal training of distance runners. *J Sports Sci* 1995;13:463-70.

[92] Hopker J, Coleman D, Passfield L. Changes in cycling efficiency during a competitive season. *Med Sci Sports Exerc* 2009;41:912-9.

[93] Bale P, Rowell S, Colley E. Anthropometric and training characteristics of female marathon runners as determinants of distance running performance. *J Sports Sci* 1985;3:115-26.

[94] Karp JR. Training characteristics of qualifiers for the U.S. Olympic Marathon Trials. *Int J Sports Physiol Perform* 2007;2:72-92.

[95] Scrimgeour AG, Noakes TD, Adams B, Myburgh K. The influence of weekly training distance on fractional utilization of maximum aerobic capacity in marathon and ultramarathon runners. *Eur J Appl Physiol Occup Physiol* 1986;55:202-9.

[96] Sjödin B, Svedenhag J. Applied physiology of marathon running. *Sports Med* 1985;2:83-99.

[97] Knechtle B, Wirth A, Knechtle P, Rosemann T. Training volume and personal best time in marathon, not anthropometric parameters, are associated with performance in male 100-km ultrarunners. *J Strength Cond Res* 2010;24:604-9.

[98] Knechtle B, Knechtle P, Rüst CA, et al. Finishers and nonfinishers in the 'Swiss Cycling Marathon ' to qualify for the 'Race Across America '. *J Strength Cond Res* 2011;25:3257-63.

[99] Knechtle B, Knechtle P, Rüst CA, et al. Age, training, and previous experience predict race performance in long-distance inline skaters, not anthropometry. *Percept Mot Skills* 2012;114:141-56.

[100] Knechtle B, Rüst CA, Knechtle P, Rosemann T. Does muscle mass affect running times in male long-distance master runners? *Asian J Sports Med* 2012;3:247-56.

[101] Yeung SS, Yeung EW, Wong TW. Marathon finishers and non-finishers characteristics. A preamble to success. *J Sports Med Phys Fitness* 2001;41:170-6.

[102] Schabort EJ, Killian SC, St Clair Gibson A, et al. Prediction of triathlon race time from laboratory testing in national triathletes. *Med Sci Sports Exerc* 2000;32:844-9.

[103] McKelvie SJ, Valliant PM, Asu ME. Physical training and personality factors as predictors of marathon time and training injury. *Percept Mot Skills* 1985;60:551-66.

[104] Roecker K, Schotte O, Niess AM, et al. Predicting competition performance in long-distance running by means of a treadmill test. *Med Sci Sports Exerc* 1998;30:1552-7.

[105] Scott BK, Houmard JA. Peak running velocity is highly related to distance running performance. *Int J Sports Med* 1994;15:504-7.

[106] Van Schuylenbergh R, Eynde BV, Hespel P. Prediction of sprint triathlon performance from laboratory tests. *Eur J Appl Physiol* 2004;91:94-9.

[107] Knechtle B, Wirth A, Rosemann T. Predictors of race time in male ironman triathletes: physical characteristics, training, or prerace experience? *Percept Mot Skills* 2010;111:437-46.

[108] Mahon AD, Del Corral P, Howe CA, et al. Physiological correlates of 3-kilometer running performance in male children. *Int J Sports Med* 1996;17:580-4.

[109] Knechtle B, Wirth A, Knechtle P, Rosemann T. Moderate association of anthropometry, but not training volume, with race performance in male ultraendurance cyclists. *Res Q Exerc Sport* 2009;80:563-8.

[110] Knechtle B, Baumgartner S, Knechtle P, et al. Changes in skinfolds and body fat in ultra-marathoners. *Open Access J Sports Med* 2012;3:147-57.

[111] Legaz A, Eston R. Changes in performance, skinfold thicknesses, and fat patterning after three years of intense athletic conditioning in high level runners. *Br J Sports Med* 2005;39:851-6.

[112] Dolgener FA, Kolkhorst FW, Whitsett DA. Long slow distance training in novice marathoners. *Res Q Exerc Sport* 1994;65:339-46.

[113] Legaz Arrese A, González Badillo JJ, Serrano Ostáriz E. Differences in skinfold thicknesses and fat distribution among top-class runners. *J Sports Med Phys Fitness* 2005;45:512-7.

[114] Leake CN, Carter JE. Comparison of body composition and somatotype of trained female triathletes. *J Sports Sci* 1991;9:125-35.

[115] Martinsen M, Bratland-Sanda S, Eriksson AK, Sundgot-Borgen J. Dieting to win or to be thin? A study of dieting and disordered eating among adolescent elite athletes and non-athlete controls. *Br J Sports Med* 2010;44:70-6.

[116] Martinsen M, Sundgot-Borgen J. Higher prevalence of eating disorders among adolescent elite athletes than controls. *Med Sci Sports Exerc* 2013;45:1188-97.

[117] Sundgot-Borgen J, Torstveit MK. Prevalence of eating disorders in elite athletes is higher than in the general population. *Clin J Sport Med* 2004;14:25-32.

[118] Zillmann T, Knechtle B, Rüst CA, et al. Comparison of training and anthropometric characteristics between recreational male half-marathoners and marathoners. *Chin J Physiol* 10.4077/CJP.2013.BAB105

[119] O'Toole ML. Training for ultraendurance triathlons. *Med Sci Sports Exerc* 1989;21:S209-13.

[120] Knechtle B, Wirth A, Knechtle P, et al. A comparison of ultra-endurance cyclists in a qualifying ultra-cycling race for Paris-Brest-Paris and Race Across America-Swiss cycling marathon. *Percept Mot Skills* 2012;114:96-110.

[121] Siders WA, Lukaski HC, Bolonchuk WW. Relationships among swimming performance, body composition and somatotype in competitive collegiate swimmers. *J Sports Med Phys Fitness* 1993;33:166-71.

[122] Helgerud J, Ingjer F, Strømme SB. Sex differences in performance-matched marathon runners. *Eur J Appl Physiol Occup Physiol* 1990;61:433-9.

[123] Sparling PB, Cureton KJ. Biological determinants of the sex difference in 12-min run performance. *Med Sci Sports Exerc* 1983;15:218-23.

[124] Knechtle B, Knechtle P, Rosemann T, Senn O. Sex differences in association of race performance, skin-fold thicknesses, and training variables for recreational half-marathon runners. *Percept Mot Skills* 2010c;111:653-68.

[125] Rüst CA, Knechtle B, Knechtle P, Rosemann T. A comparison of anthropometric and training characteristics between recreational female marathoners and recreational female Ironman triathletes. *Chin J Physiol* 2013;56:1-10.

[126] Lepers R, Knechtle P, Knechtle B, Rosemann T. Analysis of ultra-triathlon performances. *Open Access J Sports Med* 2011;2:131-6.

[127] Gulbin JP, Gaffney PT. Ultraendurance triathlon participation: typical race preparation of lower level triathletes. *J Sports Med Phys Fitness* 1999;39:12-5.

[128] Christensen CL, Ruhling RO. Physical characteristics of novice and experienced women marathon runners. *Br J Sports Med* 1983;17: 166-71.

[129] Herbst L, Knechtle B, Lopez CL, et al. Pacing strategy and change in body composition during a Deca Iron triathlon. *Chin J Physiol* 2011;54:255-63.

[130] Sleivert GG, Wenger HA. Physiological predictors of short-course triathlon performance. *Med Sci Sports Exerc* 1993;25:871-6.

[131] Laursen PB, Rhodes EC. Factors affecting performance in an ultraendurance triathlon. *Sports Med* 2001;31:195-209.

[132] Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol* 2008;586:35-44.

[133] Ramsbottom R, Nute MG, Williams C. Determinants of five kilometre running performance in active men and women. *Br J Sports Med* 1987;21:9-13.

[134] Takeshima N, Tanaka K. Prediction of endurance running performance for middle-aged and older runners. *Br J Sports Med* 1995;29:20-3.

[135] Tanaka K, Mimura K, Kim HS, et al. Prerequisites in distance running performance of female runners. *Ann Physiol Anthropol* 1989; 8:79-87.

[136] Loftin M, Sothern M, Koss C, et al. Energy expenditure and influence of physiologic factors during marathon running. *J Strength Cond Res* 2007;21:1188-91.

[137] Legaz Arrese A, Munguía Izquierdo D, Serveto Galindo JR. Physiological measures associated with marathon running performance in high-level male and female homogeneous groups. *Int J Sports Med* 2006;27:289-95.

[138] Davies CT, Thompson MW. Aerobic performance of female marathon and male ultramarathon athletes. *Eur J Appl Physiol Occup Physiol* 1979;41:233-45.

[139] Billat VL, Demarle A, Slawinski J, et al. Physical and training characteristics of top-class marathon runners. *Med Sci Sports Exerc* 2001;33:2089-97.

[140] Joyner MJ. Modeling: optimal marathon performance on the basis of physiological factors. *J Appl Physiol* 1991;70:683-7.

[141] Nicholson RM, Sleivert GG. Indices of lactate threshold and their relationship with 10-km running velocity. *Med Sci Sports Exerc* 2001;33:339-42.

[142] Grant S, Craig I, Wilson J, Aitchison T. The relationship between 3 km running performance and selected physiological variables. *J Sports Sci* 1997;15:403-10.

[143] Stratton E, O'Brien BJ, Harvey J, et al. Treadmill velocity best predicts 5000-m run performance. *Int J Sports Med* 2009;30:40-45.

[144] McLaughlin JE, Howley ET, Bassett DR Jr, et al. Test of the classic model for predicting endurance running performance. *Med Sci Sports Exerc* 2010;42:991-7.