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# Laufökonomie
# Ein unterschätzter Faktor für Amateursportler?

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## Widmung

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## Zusammenfassung deutsch

Die Laufökonomie erfasst den Wirkungsgrad der kardiometabolischen Energiebereitstellung eines Menschen für die bipedale Fortbewegung. Ob diese, im Leistungssport häufig angewandte, Größe auch bei Amateursportlern ein leistungsbeeinflussender Faktor ist, wurde bislang noch nicht systematisch untersucht. Speziell die großen Leistungsunterschiede bei Amateursportlern und die Vielzahl an Erfassungs- und Auswertungsmethoden stellen für die interindividuelle Vergleichbarkeit in diesem Kollektiv bislang noch ungelöste Probleme dar.

Die vorliegende Untersuchung verfolgt drei Ziele: 1) Die Überprüfung der Eignung standardisierter stufenförmiger Belastungsprotokolle zur Laufökonomieermittlung; 2) Die Analyse des Einflusses der relativen Beanspruchungsintensität auf die Laufökonomie; und 3) Den Nachweis der Bedeutung der Laufökonomie für die Laufleistung von Amateursportlern unterschiedlicher Leistungsfähigkeit. Zu diesem Zweck wurden zwei unabhängige Studien im Querschnittdesign entworfen. Das erste Experiment überprüfte die Eignung spiroergometrischer Kenngrößen aus stufenförmigen Belastungstests zur Bestimmung der Laufökonomie und deren Einflüsse auf die Laufleistung bei Amateursportlern. Die zweite dieser Arbeit zugrundeliegende Studie diente zur Identifikation des optimalen Beanspruchungsniveaus zur zuverlässigen Bestimmung von Parametern der Laufökonomie bei Amateursportlern.

Die vorliegenden Ergebnisse deuten darauf hin, dass stufenförmige Belastungsprotokolle zur Laufökonomieermittlung an definierten Beanspruchungspunkten geeignet sind. Sie bestätigen den Einfluss der Laufökonomie auf die Laufleistung bei Amateursportlern unabhängig von der maximalen Sauerstoffaufnahme. Die Auswertung als Sauerstoff- (ml/kg/m) und/oder Kalorienumsetzung (kcal/kg/km) pro zurückgelegte Strecke an standardisierten submaximalen Referenzpunkten erscheint im Amateurbereich

empfehlenswert. Speziell für Amateursportler können diese Größen nicht nur als leistungslimitierender Faktor interpretiert sondern auch zur Quantifizierung des bewegungsbezogenen Energieverbrauchs und des damit assoziierten Gesundheitsnutzen körperlicher Aktivität herangezogen werden.

## Zusammenfassung englisch

Running Economy assessment is an approach to convert gross aerobic capacity into net performance output during endurance running. It is often prescribed as a key quality of running performance for elite athletes. However, its influence on submaximal running performance in recreational distance runners is unclear. Furthermore, due to a variety of available assessment methods the evaluation and in particular interindividual comparability is limited.

The aim of this study was to evaluate the feasibility of individual threshold based assessment approaches and the influence of running economy on running performance of recreational runners. Two independent cross-sectional studies were conducted. The first experiment evaluated the feasibility of running economy assessment within routine cardiopulmonary exercise testing and the influence on running performance in amateur runners. The second study compared two measures of running economy, (oxygen cost in ml/kg/km and caloric unit cost in kcal/kg/km) at individual respiratory determined thresholds.

Complementing routine exercise testing with running economy assessment seems feasible. Oxygen cost and caloric cost can be assessed as markers for running economy at individual threshold intensities for amateur athletes. Furthermore, this study provides evidence that running economy influences submaximal running performance in recreational distance runners within a broad range of maximal aerobic capacity. Running economy data can be used to supplement running performance evaluation and to quantify physical activity related energy expenditure.

# Übergreifende Zusammenfassung

## Einleitung

Ausdauersportarten sind aufgrund der gesundheitsförderlichen Relevanz und des stetig wachsenden Interesses der Bevölkerung von zentraler Bedeutung für die sportmedizinische Diagnostik und Bewegungsberatung. In diesem Kontext stellt die Objektivierung der körperlichen Leistung und Funktion eine relevante Grundlage zur Bewertung des Gesundheits- und Trainingszustands als auch zur Trainingssteuerung und Evaluation von Therapie- und Präventionsprogrammen dar.

Mittels sportartspezifischer spiroergometrischer Untersuchungen können verlässliche Aussagen zur Ausdauerleistungsfähigkeit getätigt und Informationen zum Energiestoffwechsel während körperlicher Belastung getroffen werden.
Eine zielführende und umfassende Diagnostik zur Objektivierung der körperlichen Leistung und Funktion steht hierbei auf drei Grundpfeilern: der Erfassung der maximalen Sauerstoffaufnahmekapazität (VO2max), der Detektion relevanter Stoffwechselveränderungen bei zunehmender Beanspruchung (submaximale Beanspruchungsparameter) und der Quantifizierung des Energieumsatzes [1].

Für die Quantifizierung des Energieumsatzes werden sowohl Verfahren verwendet, welche die umgesetzte Energiemenge pro Zeiteinheit abbilden als auch Verfahren, die den energetischen Aufwand in Relation zur zurückgelegten Strecke setzen [2]. Hierbei kann die umgesetzte Energiemenge pro Strecke als relative Sauerstoffaufnahme pro gelaufene Strecke (ml/kg/km) und als Kalorienumsatz pro gelaufene Strecke (kcal/kg/km) angegeben und als Messgröße der Laufökonomie interpretiert werden. Neben der Quantifizierung des Energieumsatzes ergibt sich somit die Möglichkeit der Ermittlung des Wirkungsgrades der kardiometabolischen Energiebereitstellung für die Fortbewegung. Aus Untersuchungen an Leistungssportlern lässt sich ableiten, dass die Bewegungsökonomie insbesondere beim Laufsport (Laufökonomie), eine nicht zu vernachlässigende Bedeutung für die Leistungsfähigkeit hat [3].

Trotz der großen Zahl an Laufsportausübenden (ca. 10 Millionen in Deutschland) [4] ist bislang die Übertragung der im Leistungssport regelmäßig angewandten Kenngrößen und Auswertungsmethoden zur Laufökonomiebestimmung in den Amateurbereich nicht ausreichend erfolgt. Dies steht der Tatsache gegenüber, dass die notwendigen Daten für eine entsprechende Analyse vielerorts bei Amateursportlern während einer Ausdauerleistungsdiagnostik bereits erfasst werden.

Wenngleich die Daten häufig verfügbar sind, erfordert der Amateursportbereich, aufgrund großer interindividueller Unterschiede in Leistung und Anthropometrie, besondere Beachtung bei der Datenauswertung und Interpretation. Während im Leistungs- und Hochleistungsbereich häufig fest definierte Geschwindigkeiten eingesetzt werden um die Laufökonomie zu ermitteln [3], kann dieses Verfahren bei einem heterogenerem Kollektiv von Amateurläufern zu deutlich eingeschränkter Vergleichbarkeit und Aussagekraft führen [5,6]. Hierbei hervorzuheben, ist der mögliche Einfluss der individuellen metabolischen Beanspruchung auf die spiroergometrisch ermittelte Laufökonomie [5,7]. Überdies existieren unterschiedliche Messgrößen, die als Maß der Laufökonomie Verwendung finden. Sowohl die Erfassung der Sauerstoffaufnahme in Millilitern pro Kilogramm Körpergewicht pro gelaufenen Kilometer (ml/kg/km) als auch die Ermittlung des Energieverbrauchs in Kilokalorien pro Kilogramm Körpergewicht pro gelaufenen Kilometer (kcal/kg/km) finden parallel Anwendung [7]. Einige Autoren stellen zusätzlich infrage, ob ein linearer Zusammenhang zwischen dem Körpergewicht und der Sauerstoffaufnahme ($ml/kg^1$) im Rahmen der Laufökonomieermittlung geeignet ist [8,9] oder eine Skalierung mittels Potenzfunktion (artifiziell bestimmt, $ml/kg^{-0,75}$) verwendet werden sollte [7,10]. Überdies liegen nur eingeschränkt Kennwerte für dieses Kollektiv vor, um die individuell ermittelte Laufökonomie zu bewerten [2].

**Fragestellung**

Der aktuelle Kenntnisstand hinsichtlich der Erfassung und Bedeutung der Laufökonomie bei Amateursportlern resultiert in offenen Fragen. Bislang fehlt der systematische Nachweis der Anwendbarkeit der oben genannten Verfahren. Überdies ist das Bedeutungsausmaß des Faktors Laufökonomie auf die Laufleistung bei Amateursportlern mit unterschiedlicher Leistungsfähigkeit nicht systematisch analysiert.

Vor dem dargelegten Hintergrund verfolgt die vorliegende Dissertationsschrift drei Ziele.

1) Die Überprüfung der Eignung standardisierter stufenförmiger Belastungsprotokolle zur Laufökonomieermittlung.

2) Die Analyse des Einflusses der relativen Beanspruchungsintensität auf die Laufökonomie.

3) Den Nachweis der Bedeutung der Laufökonomie für die Laufleistung von Amateursportlern unterschiedlicher Leistungsfähigkeit.

**Darstellung Manuskript I - Laufökonomieermittlung während standardisierter Belastungsuntersuchungen bei Amateursportlern**

Ziele der im Folgenden beschriebenen Studie im Querschnittdesign sind die Untersuchung der Eignung spiroergometrischer Kenngrößen aus stufenförmigen Belastungstests zur Bestimmung der Laufökonomie und deren Einflüsse auf die Laufleistung bei Amateursportlern in Abhängigkeit der kardiorespiratorischen Leistungsfähigkeit.

Achtundsechzig Amateursportler (19 ♀; 21-54 Jahre; Größe 178 ± 9 cm, Gewicht 75,5 ± 11,6 kg) absolvierten einen stufenförmigen Ausbelastungstest auf einem Laufband (Stufendauer 4 min, Inkrement 1,5 km/h, 0 % Steigung). Die maximale Sauerstoffaufnahme und der respiratorische Kompensationspunkt wurden mittels Spiroergometrie erfasst und bestimmt. Die Laufökonomie wurde als relative Sauerstoffaufnahme pro Kilogramm Körpergewicht pro gelaufene Strecke (ml/kg/km) anhand der Messwerte der Stufe unterhalb des respiratorischen Kompensationspunktes berechnet. Die maximale Sauerstoffaufnahme wurde anhand einer international etablierten Klassifikation alters- und geschlechtsspezifisch in vier Fitnesslevel (fair, good, excellent, superior) eingeteilt [11]. Die Laufökonomie wurde durch Mediansplit der Gesamtgruppe in zwei Subpopulationen (über- vs. unterdurchschnittlich) stratifiziert (Median = 215,28 ml/kg/km). Die statistische Prüfung auf Unterschiede erfolgte unter Verwendung nichtparametrischer Prüfverfahren (Signifikanzniveau 5%).

Die maximale Sauerstoffaufnahme lag im Mittel bei 47,4 ± 7,4 ml/kg/min. Unabhängig der Einteilung in Fitnesslevel erzielten Probanden mit ökonomischerem Laufstil (<215,28 ml/kg/km) eine im Vergleich signifikant höhere Geschwindigkeit am respiratorischen Kompensationspunkt (12,2 ± 1,4 vs. 10,8 ± 2,0 km/h). Innerhalb der Fitnesslevel „good“ und „superior“ waren signifikante Unterschiede der Laufgeschwindigkeit am respiratorischen Kompensationspunkt in Abhängigkeit der Laufökonomie nachweisbar. Zwischen den Gruppen wurden keine Unterschiede im Alter, der Körpergröße, im Körpergewicht oder Body-Mass-

Index gefunden. Es lag keine signifikante Korrelation zwischen den am Körpergewicht relativierten Laufökonomiewerten (ml/kg/km) und dem Körpergewicht vor (r=0,221).

Basierend auf den in der regulären spiroergometrischen Testung generierten Parametern kann durch einfache Bestimmung von Quotienten der Faktor Laufökonomie berechnet werden. Diese somit ohne Zusatzaufwand ermittelten Daten der Laufökonomie zeigen bei Amateursportlern unterschiedlicher Leistungsfähigkeit einen Einfluss auf die Laufleistung. Das Körpergewicht scheint im untersuchten Kollektiv als Bezugsmaß für die einfache allometrische Skalierung ($ml/kg^1$) geeignet.
Die Berechnung der Laufökonomie anhand der durch einen stufenförmigen Belastungstests gewonnenen Daten kann somit in der sportmedizinischen Diagnostik zu einer differenzierteren Betrachtung der individuellen bewegungsspezifischen Leistungsfähigkeit beitragen ohne zusätzlichen Messaufwand oder eine erhöhte Belastung für den Amateursportler zu verursachen.

**Darstellung Manuskript II - Intensitätsabhängige Unterschiede der Laufökonomie bei Amateursportlern**

Die im folgenden Kapitel beschriebene Querschnittstudie dient zur Bestimmung des optimalen Beanspruchungsniveaus zur zuverlässigen Ermittlung von Parametern der Laufökonomie bei Amateursportlern. Kontrastierend untersucht wird der Zusammenhang zweier etablierter Größen der Laufökonomie bei definierten Beanspruchungen mit der Laufleistung.

Achtzehn Amateursportler (7 ♀; 19 - 30 Jahre; Größe 175 ± 7 cm; Gewicht 67,1 ± 7,5 kg) absolvierten einen rampenförmigen Ausbelastungstest sowie einen dreistufigen Test auf einem Laufband im Abstand von mindestens 48h. Die maximale Sauerstoffaufnahme sowie die ventilatorischen Schwellen (erste ventilatorische Schwelle und respiratorischer Kompensationspunkt) wurden mittels Spiroergometrie im rampenförmigen Test bestimmt.

Als Punkte vergleichbarer Beanspruchung für die Laufökonomieermittlung mittels dreistufigem Test dienten die Laufgeschwindigkeiten aus dem Ausbelastungstest an der ersten ventilatorischen Schwelle, am respiratorischen Kompensationspunkt und im mittleren Bereich des aerob-anaeroben-Übergangs. Die Laufökonomie wurde auf allen drei Stufen als relative Sauerstoffaufnahme pro gelaufene Strecke (ml/kg/km, Sauerstoff-Ökonomie) und als Kalorienumsatz pro gelaufene Strecke (kcal/kg/km, Kalorien-Ökonomie) ermittelt. Für die Analysen wurden Varianzanalysen und T-Tests mit Bonferroni-Holm α-Fehler-Adjustierung sowie parametrische Korrelationen angewendet (Signifikanzniveau 5%).

Die mittlere VO2max lag bei 53,2 ± 5,8 ml/kg/min. Die an den drei Beanspruchungspunkten ermittelten Werte der Laufökonomie standen wechselseitig in hohem linearen Zusammenhang. Separate Varianzanalysen zeigten signifikante Unterschiede der Sauerstoff- (Analyse I) und Kalorien-Ökonomiewerte (Analyse II) an den drei Beanspruchungspunkten. Erste ventilatorische Schwelle: Geschwindigkeit 8,7 ± 1,0 km/h; Sauerstoff-Ökonomie

235,4 ± 26,2 ml/kg/min; Kalorien-Ökonomie 1,18 ± 0,13 kcal/kg/km. Aerob-anaerober-Bereich: Geschwindigkeit 10,5 ± 1,2 km/h; Sauerstoff-Ökonomie 227,8 ± 23,4 ml/kg/min; Kalorien-Ökonomie 1,14 ± 0,12 kcal/kg/km. Respiratorischer Kompensationspunkt: Geschwindigkeit 11,9 ± 1,7 km/h; Sauerstoff-Ökonomie 224,9 ± 21,9 ml/kg/min; Kalorien-Ökonomie 1,13 ± 0,11 kcal/kg/km.
Kontrolliert für den Einfluss des Faktors Geschlecht konnte ein signifikanter Zusammenhang zwischen den Laufökonomiewerten und der Laufgeschwindigkeit am Punkt der maximalen Sauerstoffaufnahme sowie der Laufgeschwindigkeit am respiratorischen Kompensationspunkt detektiert werden. Zwischen der maximalen Sauerstoffaufnahme und der Laufökonomie bestand kein signifikanter Zusammenhang.

Die abnehmenden Laufökonomiewerte mit zunehmender Beanspruchung deuten auf einen höheren anaeroben Anteil an der Energiebereitstellung und auf den Einfluss der physiologischen Stoffwechselsituation auf die spiroergometrie-basierte Erfassung der Laufökonomie hin. Für den interindividuellen Vergleich der laufspezifischen Bewegungsökonomie bei Amateursportlern scheint daher die Nutzung von physiologischen Schwellenkonzepten notwendig. Überdies konnte nachgewiesen werden, dass bei diesem Kollektiv ein deutlicher Zusammenhang zwischen Laufökonomie und Laufgeschwindigkeit an leistungsrelevanten metabolischen Referenzpunkten besteht.

**Diskussion**

Die vorliegenden Ergebnisse deuten darauf hin, dass stufenförmige Belastungsprotokolle zur Laufökonomieermittlung an definierten Beanspruchungspunkten geeignet sind und belegen die Relevanz der Laufökonomie für die Laufleistung von Amateursportlern. Diesbezüglich sind die zentralen Erkenntnisse aus den vorliegenden Studien: 1) Die bei vergleichbarer Beanspruchung in einem standardisierten Belastungsprotokoll erreichte Laufökonomie unterscheidet sich nicht signifikant zwischen verschiedenen Leistungsklassen; 2) Die Laufökonomie an unterschiedlichen Punkten der individuellen Beanspruchung unterscheidet sich signifikant; und 3) Die Laufökonomie zeigt bei Amateurläufern unterschiedlicher Leistungsklassen einen signifikanten Einfluss auf die Laufleistung.

Die gewonnenen Erkenntnisse veranschaulichen, dass die im Rahmen einer sportartspezifischen stufenförmigen Belastungsuntersuchung gewonnenen Daten (Studie I) geeignet sind um aussagekräftige Laufökonomiewerte abzuleiten. Weiterhin belegen die Ergebnisse, dass die Bestimmung der Laufökonomie einen Nutzen bei der sportartspezifischen Leistungsbewertung für Amateure mit mittlerer und hoher kardiorespiratorischer Fitness bietet. Neben den Bruttokriterien der Ausdauerleistungsfähigkeit (maximale Sauerstoffaufnahme, Detektion relevanter Stoffwechselveränderungen bei zunehmender Beanspruchung) kann der Untersucher mittels Angabe der Laufökonomie als Sauerstoffaufnahme pro gelaufenem Kilometer (ml/kg/km) Aussagen über die Umsetzung des metabolischen Potentials in eine Laufbewegung treffen. Zusätzlich kann auf Basis der benötigten Energie pro Kilometer (kcal/kg/km) der Energieumsatz anschaulich quantifiziert werden. So ist es möglich darzustellen wie hoch der Energieverbrauch einer Trainingseinheit oder eines Wettkampfes ist. Diese Information ist sowohl für leistungsorientierte Amateursportler nutzbar um die Verpflegung während Wettkampf oder Training zu kalkulieren als auch für gesundheitsorientierte Sportler. Diese können so einen Überblick über den bewegungsbezogenen Energieverbrauch und den damit assoziierten Gesundheitsnutzen gewinnen. Im

Vergleich zur Darstellung in Form der Sauerstoffaufnahme oder Energieumsatz pro Zeiteinheit (ml/kg/min; kcal/kg/min) kann so die Bedeutung von zurückgelegter Strecke und individueller Beanspruchung während der Trainingseinheit veranschaulicht werden.

Neben dem Nachweis der Relevanz der Laufökonomie bei Amateursportlern bieten die vorliegenden Daten einen ersten Ansatz zur Bewertung der Laufökonomie. Hierzu kann der in der Studie I erfolgte Mediansplit (215,3 ml/kg/min), der anhand der Daten eines stufenförmigen Belastungsprotokolls ermittelt wurde [12], für die Einteilung der Laufökonomie in zwei Kategorien genutzt werden. Die Ergebnisse der zweiten vorliegenden Untersuchung weisen darauf hin, dass diese Werte nur für die gewählte Beanspruchung am respiratorischen Kompensationspunkt angewandt werden können. Wie der direkte Vergleich der Laufökonomie an unterschiedlichen Beanspruchungspunkten zeigt, ist für eine standardisierte Ermittlung der Laufökonomie bei Amateursportlern unterschiedlicher Leistungsfähigkeit die Auswertung an fest definierten submaximalen Referenzpunkten empfehlenswert. Infrage kommen dabei sowohl die erste als auch die zweite untersuchte metabolische Schwellenreaktion. Für die Ableitung von Referenzwerten ist insbesondere im Bereich der ersten ventilatorischen Schwelle die Fallzahl der vorliegenden Studien zu erweitern.

Im direkten Vergleich unterscheiden sich die an vergleichbaren Beanspruchungspunkten ermittelten Laufökonomiewerte aus Studie I [12] und Studie II [13]. Mögliche Erklärungsansätze hierfür bieten die Unterschiede des Probandenkollektivs und Studiendesigns. Während eine der vorliegenden Studien (I) Laufökonomiewerte aus einem stufenförmig ansteigenden Belastungsprotokoll (4 min pro Stufe) ermittelt hat [12], wurde im zweiten Experiment die Laufökonomie in drei vorab ermittelten Beanspruchungspunkten in einem separaten Test mit längerer Belastungsdauer bestimmt (6 min pro Beanspruchungspunkt) [13].
Die in der Studie I mittels Stufenprotokoll an 68 Amateurläufern (VO2max: 47,4 ± 7,4 ml/kg/min) erfassten Laufökonomiewerte (RE: 215,2 ± 18,1 ml/kg/km) [12] sind

mit den Werten aus methodisch ähnlichen Studien vergleichbar. So erreichen 16 männliche Leistungssportler (VO2max: 66,5 ± 5,6 ml/kg/min) in einer Studie von Fletcher und Kollegen Laufökonomiewerte im Bereich zwischen circa 205 und 235 ml/kg/km [5]. Weiterhin erreichen 172 Leistungssportler (VO2max: 69,5 ± 6,5 ml/kg/min) in einer ebenfalls methodisch vergleichbar angelegten Studie Laufökonomiewerten zwischen circa 200 und 235 ml/kg/km [7]. Exakte Werte lassen sich in den zitierten Studien [5,7] aufgrund der grafischen Darstellung der Wertebereiche nicht ermitteln. Im Gegensatz dazu erzielen, in der zweiten dieser Dissertation zugrundeliegenden Untersuchung, 18 junge gesunde Amateursportler (VO2max: 53,2 ± 5,8 ml/kg/km) höhere Laufökonomiewerte (224,9 ± 21,9 ml/kg/km) bei vergleichbarer Beanspruchungsintensität [13]. Die Ergebnisse aller hier aufgeführten Studien liegen gemäß einer aktuell verfügbaren Bewertungsskala für leistungsorientierte Sportler [14] im deutlich unterdurchschnittlichen Bereich (> 200 ml/kg/km). Welches Belastungsprotokoll und welches Probandenkollektiv wiederum diesen publizierten Referenzwerten zugrunde liegen, ist leider nicht dokumentiert. Im Gegensatz dazu berichtet eine aktuelle Übersichtsstudie deutlich höhere mittlere Laufökonomiewerte als Normalbereich für Amateure (10 km/h: Frauen 226 ml/kg/km, Männer 220 ml/kg/km), während die Werte für Elitesportler deutlich niedriger ausfallen (14 km/h: Frauen 179 ml/kg/km, Männer 171 ml/kg/km) [2]. Die Dokumentation der zugrundeliegenden Belastungsprotokolle ist neben der Beschreibung des untersuchten Kollektivs somit essentiell für die Bewertung von Laufökonomiedaten und die Anwendung von Referenzwerten.

Eine Stärke der vorliegenden Studien ist die praxisnahe Methodik der Laufökonomieermittlung anhand von Parametern aus standardisierten stufenförmigen Belastungstests bei Amateursportlern. Mittels der in Studie I angewandten einfachen Algorithmen können ohne Zusatzbelastung für den Probanden leistungsdeterminierende Größen bestimmt und zusätzliche Empfehlungen für die Trainingspraxis abgeleitet werden. Überdies können auf Basis eines stufenförmigen Belastungstests zusätzlich laktatbasierte aerobe und anaerobe Schwellenreaktionen erfasst werden. Inwieweit diese ebenfalls als

Referenzpunkte zur Laufökonomieermittlung bei Amateursportlern geeignet sind, sollte in zukünftigen Studien überprüft werden. Eine Schwäche der ersten vorliegenden Studie ist die alleinige Interpretation der maximalen Sauerstoffaufnahmewerte mittels der Einteilung in alters- und geschlechtsspezifische Fitnesslevel [11]. Als leistungsbezogener Kennwert, der einen direkten Vergleich mit der ermittelten Laufökonomie ermöglicht, sollte die zusätzliche Angabe der relativen Sauerstoffaufnahme (ml/kg/min) erfolgen.

Zusammenfassend deuten die vorliegenden Ergebnisse darauf hin, dass die etablierten stufenförmigen Belastungsprotokolle eine zuverlässige und für die Berechnung einfach nutzbare Datenbasis zur Laufökonomieermittlung an definierten Beanspruchungspunkten liefern. Speziell für Amateursportler kann die Laufökonomie nicht nur als leistungslimitierender Faktor interpretiert sondern auch zur Quantifizierung des bewegungsbezogenen Energieverbrauchs und des damit assoziierten Gesundheitsnutzen körperlicher Aktivität herangezogen werden. Weitere Studien sind notwendig, um die Aussagekraft von auf dem Laufband ermittelten Werten für die Laufökonomie im Freien auch bei Amateursportlern zu bestätigen und exakte Referenzwerte für die Bewertung zu definieren.

# Übersicht der zur Veröffentlichung angenommenen Manuskripte

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# Manuskript I - Running economy assessment within cardiopulmonary exercise testing for recreational runners

*Submission Type:* Original Investigation

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The research was conducted at the facilities of the Department of Sports Medicine.

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*Preferred running head:* Running economy assessment within cardiopulmonary exercise testing

# Manuskript I - Running economy assessment within cardiopulmonary exercise testing for recreational runners

## Abstract

***Background:*** The aim of this study was to evaluate 1) The influence of Running Economy (RE) on running performance within recreational runners of different maximal aerobic capacity and 2) The feasibility of RE assessment within routine cardiopulmonary exercise testing (CPET).

***Methods:*** Sixty-eight recreational runners (m: 49, f: 19; age: 21-54) completed a graded exercise test (GXT) until exhaustion. Maximal oxygen uptake and respiratory compensation point were obtained via CPET. RE was calculated as relative oxygen uptake per covered distance (ml/kg/km) one step below respiratory compensation point (RCP). Subjects were grouped for RE via median split and categorized into one of six fitness levels (Very Poor, Poor, Fair, Good, Excellent, Superior) (ACSM 2010).

***Results:*** Irrespective of fitness levels, recreational runners with a more energy efficient movement (RE<215.28 ml/kg/km) reached a significant ($p<.05$) higher velocity at RCP (12.2 vs. 10.8 km/h). The measured $VO_{2max}$ values ranged between 35.2 and 66.0 ml/min/kg. Running velocity at RCP of runners within $VO_{2max}$ categories Good and Superior differed significantly ($p<.05$) between RE groups.

***Conclusions:*** This study provides evidence that RE influences submaximal running performance in recreational distance runners within a broad range of maximal aerobic capacity. Complementing routine CPET with RE assessment at physiological threshold intensities and ACSM based categorization seems feasible to delineate the impact of movement efficiency and aerobic fitness on performance in recreational runners.

## Introduction

Running specific efficiency of movement, often referred to as Running Economy (RE), indicates the ability to transfer aerobic power into locomotion speed over ground. In particular, the rate of oxygen an individual consumes at a given speed is reported to be a strong determinant of running performance [1]. Beside the work to increase and sustain running velocity the body executes numerous other essential processes during movement. The terms “efficient” or “running efficiency” are therefore not as appropriate as “economy” [2].Thus RE is an approach to convert gross capacity to net performance output.

Many studies have highlighted the important role of RE for racing ability and have already applied methods for the examination within elite athletes of almost comparable aerobic performance [3–6]. The maximal oxygen uptake ($VO_{2max}$) [7,8,3] and the ability to sustain a high percentage of $VO_{2max}$ ($\%VO_{2max}$) for longer periods, which stands in a direct relation to maximal steady state condition of energy metabolism [9,4], are already established and frequently applied measurements in performance diagnostics for endurance athletes on elite and recreational level. By comparison limited knowledge regarding the specific influence of RE on running performance and furthermore factors affecting RE in recreational runners is available.

Many characteristics, like anthropometric data, age or sport specific physical capacities show a wide variation in recreational athletes and their influence on RE has only been reported inconsistently concerning applied methods and results [1,10–13]. Due to the broad range in performance and possible underlying mechanisms test protocols for elite athletes cannot be adopted on a one to one basis. Therefore it is of great practical relevance to define and evaluate standardized and feasible approaches to assess and differentiate the influences of RE and aerobic performance in recreational runners.

Currently a variety of non-validated methods are used for RE examination. Differences can be found regarding test protocols as well as outcome parameters. Test durations of 3-4 minutes were already used and validated [5] as an approach to evaluate RE [4] and could provide the possibility to obtain multiple relevant variables within a GXT. Some current methods use fixed running speeds for RE calculation [4], even though this has recently been criticized and the implementation of more individual approaches in order to generate comparable metabolic situations is proposed [14,15]. Furthermore a steady state condition of aerobic energy metabolism is crucial for valid RE determination [4,16]. Therefore several working groups recently recommended the application of threshold based concepts[14,17]. RE defined as oxygen uptake in milliliters per kilogram bodyweight per kilometer distance (ml/kg/km) is well established [2] and applied in recent studies [1,10,11]. However, the applicability of linear body weight scaling has to be controlled. Running speed at the respiratory compensation point (RCP) as an intensity representing the highest steady state condition of oxygen uptake [18,4] could serve as a comparable and relevant reference point for amateur runners across different performance levels [19]. $VO_{2max}$ categorization via normative values provided by the ACSM [20] is a valid approach to consider differences of aerobic performance, with specific reference to age and sex. Combining these two concepts of performance evaluation and running intensity deduction could therefore detect fitness related differences of RE within a standardized examination.

The present study investigated whether, and if so by how much, RE influences running performance in a broad variety of recreational distance runners categorized according their aerobic fitness level [20]. Furthermore we evaluated the feasibility of a single test protocol estimating running economy, maximal oxygen uptake, respiratory compensation point and oxygen uptake kinetics.

## Materials and Methods

***Subjects:*** Forty-nine male and nineteen female recreational endurance runners (age: 35.4 ± 9.0 years, body mass: 75.5 ± 11.6 kg, height: 178 ± 8.9 cm, BMI: 23.6 ± 2.7 kg/m2) participated in the study. All subjects were regularly active in running (5.0 ± 3.5h / week). Inclusion criteria were fulfilling the criteria of the “Deutsche Gesellschaft für Sportmedizin” for minimal risk of exercise 21 and individual VO2max values within the ACSM guideline for exercise testing percentile values for maximal aerobic capacity 20. The testing procedures were supervised by a physician. None of the subjects reported acute neuromuscular or musculoskeletal injuries at the time of the study. The study protocol and execution was in accordance with the Declaration of Helsinki and the principals of good clinical practice. The study was reviewed and approved by the local ethics committee under reference number 2014-89K. The runners gave their written informed consent to participate in the laboratory testing.

***Design and Methodology:*** All subjects performed a graded exercise test (GXT) on an electronically driven treadmill (Quasar med, HP Cosmos, Wuerzburg, Germany) at 0° inclination. The GXT started with a resting reference phase. The initial running velocity was individually set based on participant reports including information about average training hours per week, running experience, preferred running speed and actual competition results. The speed was increased stepwise by 1.5km/h every 4 min until volitional exhaustion.

Oxygen uptake (VO2) was measured using a breath-by-breath gas analyzer (Oxycon Mobile, Viasys Healthcare GmbH, Wuerzburg, Germany). Participants breathed through a rubber face mask (Hans Rudolph Inc., Shawnee, USA). The respired air was directed into a ventilation turbine and into the portable unit housing the $O_2$ and $CO_2$ gas analyzers. $VO_2$ and $VCO_2$ data were telemetrically transferred to a computer for further analysis. The measuring instrument was calibrated before each test using reference gases (outside air and 5% CO2, 16% O2) and automated standard ventilatory volumes (0.2 and 2 L/min). Sufficient reliability and validity of the used indirect calorimetry device have recently been demonstrated [22,23]. The oxygen data was reduced to 5 s stationary averages.

The highest 30 s floating mean of $VO_2$ within the testing time was defined as maximal oxygen uptake. All subjects met at least two of the following criteria for accepting values as maximal: 1) RER above 1.05, 2) Attainment of maximum age-predicted heart rate (HR) +/- 5%, 3) Rate of perceived exertion via Borg-Scale ≥17 (17-20). The second ventilatory threshold or RCP was independently determined by two investigators, in a double blind procedure. RCP was identified by the second non-linear increase in minute ventilation ($V_E$) and $V_E$ versus $VCO_2$ accompanied by a concomitant non-linear increase in $V_E/VCO_2$ [17,16]. Running

Economy was defined as relative oxygen uptake per covered distance (ml/kg/km), calculated from one step below RCP. After steady state of oxygen uptake during the last minute of the step was confirmed, a 30 s floating mean of oxygen uptake was used for calculation.

Subjects were classified in categories relating to their $VO_{2max}$ and in 2 groups according to their RE. Individual $VO_{2max}$ data was rated as age and gender specific percentile values of maximal aerobic capacity according to the ACSM guidelines for exercise testing and prescription [20] and provided the basis for the subsequent categorization (Very Poor, Poor, Fair, Good, Excellent, Superior). The stratification of the RE values via median split over all participants was applied in total - and subgroup-analyses. Runners with RE values above the group median value were considered less economic (RE-), Runners with RE values below were considered more economic (RE+). Subjects' achieved speed at RCP ($V_{RCP}$) was taken as evaluation criterion of submaximal running performance. Subgroup analysis was carried out according ACSM categories.

***Statistical analysis:*** For statistical analysis we used IBM SPSS statistics software (Version 21.0) for Windows and Microsoft Excel 2010. Descriptive statistics are reported as means and standard deviations. Due to the subgroup sample size Shapiro-Wilk normality tests and Levene tests for variance homogeneity were used. As data did not meet normality or variance were not homogeneous non-parametric Mann-Whitney-U-Tests were applied to test for differences in outcome measures between the RE groups. Cohen`s d and effect-sizes were calculated for an overall group comparison of RE. Relationship between ratio scaled RE values and body mass was determined using Spearman correlation coefficient. A p-value of <.05 was considered statistically significant. Due to multiple testing Bonferroni-Holm correction was applied.

## Results

Performance characteristics of runners are presented in Table 1. The median value of RE for subject dichotomization was 215.3 ml/kg/km, the mean value was 215.2ml/kg/km ± 18.1.

| ACSM MAP category | RE stratification ( + / - ) | Subjects n | VO2max (ml/min/kg) | vRCP (km/h) | RE (ml/min/kg/km) |
|---|---|---|---|---|---|
| ***fair*** | - | *7* | *42,4 ± 3,2* | *10,4 ± 1,0* | *226,3 ± 8,8* |
| ***fair*** | + | *8* | *39,7 ± 2,9* | *10,6 ± 1,7* | *196,6 ± 12,8* |
| ***good*** | - | *10* | *44,5 ± 3,8* | *10,0 ± 0,7* | *227,8 ± 10,8* |
| ***good*** | + | *10* | *44,4 ± 4,0* | *11,7 ± 1,5* | *199,5 ± 10,7* |
| ***excellent*** | - | *8* | *46,7 ± 4,1* | *10,8 ± 1,5* | *232,6 ± 14,7* |
| ***excellent*** | + | *9* | *48,2 ± 3,9* | *12,3 ± 1,2* | *203,6 ± 5,1* |
| ***superior*** | - | *9* | *55,5 ± 6,6* | *12,3 ± 1,0* | *231,9 ± 10,4* |
| ***superior*** | + | *7* | *59,4 ± 3,6* | *14,5 ± 1,4* | *203,6 ± 5,4* |

*Table 1 - Physical and performance characteristics of runners for analyzed categories (Mean ± SD), categorized due to running economy (more economic=RE+; less economic=RE-) and maximal aerobic performance (MAP) according American College of Sports Medicine (ACSM). Maximal oxygen uptake (VO2max) in milliliters per minute time per kilogram bodyweight, running speed at Respiratory Compensation Point (VRCP) in kilometers per hour, Running Economy (RE) in milliliters oxygen uptake per kilogram bodyweight per kilometer distance.*

Overall, subjects with a more energy efficient movement (RE+) (RE+:201.7 ±4.6 vs. RE-:229.7 ±3.1 ml/kg/km) reached a higher velocity at RCP (12.2 ± 1.4 vs. 10.8km/h ± 2.0; p=.000; Cohen`s d: 0.74; effect size r: 0.35). However there was no difference in mean $VO_{2max}$ values (RE+: 47.4ml/min$^{-1}$kg ± 7.8 vs. RE-: 47.5ml/min$^{-1}$kg ± 7.0; p=.893) between the two groups.

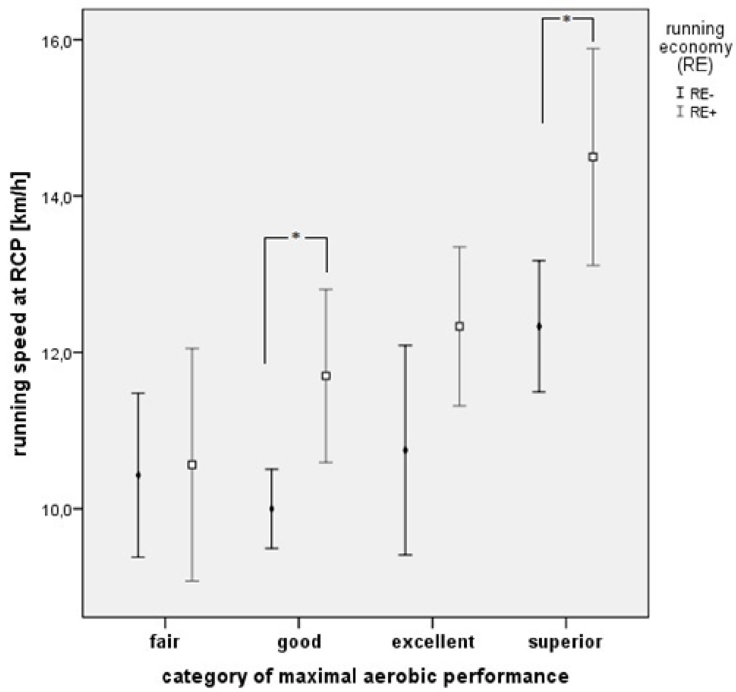


*Figure 1 – 95% confidence intervals of subjects' achieved speed at RCP ($V_{RCP}$) in kilometers per hour (km/h) over all categories of maximal aerobic performance (fair, good, excellent, superior) according to RE (more economic=RE+, less economic=RE-) including significances. *p≤.01*

Four of six ACSM categories (Fair, Good, Excellent, Superior) were filled with subjects due to the range of maximal oxygen uptake. Table one illustrates the variation of performance characteristics, including RE and running speed at RCP, among subgroups categorized due to aerobic fitness and RE (RE+; RE-). The velocities at RCP of the categories Good and Superior were significantly higher (p=.000) in the subgroup with a more energy efficient movement (RE +). There was a tendency in the category Excellent for RE+ runners to have a faster velocity ($V_{RCP}$), despite there was no statistical significance (p=.059). No differences in RE were observed between the four ACSM categories and between RE+ or RE- subgroups across different fitness levels.
No differences in $VO_{2max}$ were found between RE subgroups within each of the ACSM categories. With exception between categories Good and Excellent, adjacent age and gender related fitness level categories, differed in relative

VO2max ($p \leq .05$). No differences in age, weight, height and BMI were found between ACSM categories or RE subgroups. There was no correlation of RE and body mass ($r = .221$).

## Discussion

The aim of this study was to evaluate 1) The influence of Running Economy (RE) on running performance within recreational runners of different aerobic fitness and 2) The feasibility of RE assessment within routine cardiopulmonary exercise testing (CPET). Our results show that irrespective of their maximal aerobic capacity subjects with good RE (RE+) reached a significant higher $V_{RCP}$ and range of RE values is comparable across fitness levels. Furthermore the applied protocol, with intensity just below RCP and four minutes step duration within GXT was sufficient for RE assessment under steady state condition.

These findings indicate that RE positively affects submaximal running performance in recreational runners, which corresponds to the strong association between RE and distance running performance on elite level [24,25]. In contrast to elite, recreational athletes are more heterogeneous concerning factors like age, cardiorespiratory fitness or anthropometry. Available data acknowledge RE as an important factor for running performance [26], especially for the differentiation within homogeneous groups of comparable $VO_{2max}$ [25]. To the best of our knowledge, to date no study has investigated the influence of RE in recreational runners within subgroups of comparable aerobic fitness [20]. Therefore, we categorized the subjects based on ACSM`s age and gender related values [20] for analysis. The significant differences within the groups Good and Superior indicate that individuals with similar aerobic fitness but more efficient movement (RE+) are able to reach higher running speeds. Furthermore the tendency within the group Excellent supports the transferability of these findings on a broader range of performance levels. The lack of differences within category Fair indicates, that the influence of RE appears to be minor in runners with low aerobic performance. Overall the range of RE values seems to be wider than reported data of highly trained athletes [24]. Consequently, RE can be used as predictor of performance within recreational runners but data or classification of elite level should not be transferred on a one to one basis [15]. While subjects anthropometric and performance data differed considerably to elite level [9], no differences were found concerning age and anthropometric characteristics within subgroups. Therefore we evaluated the transferability from elite level of the applied scaling methods. There was no correlation between RE, calculated as milliliter of oxygen uptake per kilogram bodyweight per kilometer (ml/kg/km), and body mass. Therefore linear ratio scaling of RE and comparison between subgroups was appropriate. Beside the applied testing procedure, current studies use various non-validated other test protocols for RE determination. Most differences can be found regarding running speed, stage duration and data calculation. Steady state condition of oxygen uptake is crucial for RE measurement [18,4], therefore we used intensities below the second ventilatory threshold or respiratory compensation point (RCP). The application of elite level protocols with fixed reference velocities [4] and the application of a given percentage of $VO_{2max}$ for RE calculation, for recreational athletes may result in incomparable individual metabolic situations [14]. We determined RE just below individual respiratory compensation point, and therefore applied a comparable benchmark for recreational runners of different performance levels. Different methods involving stages of 4-10min duration with progressively increasing speed are used as an approach to evaluate RE [4]. In current studies shorter durations [27,28] or randomized sequences [29] are used as well. Most of the protocols are not sufficiently validated yet. We applied a reliable protocol, with 4min stage duration and data calculation from the last minute [5] and controlled steady state condition of oxygen uptake. Owing to the individual race schedules, valid competition-based indicators of performance like finish time or race splits are not available for every runner. Thus, we determined running velocity with attainment of respiratory compensation point, as a valid laboratory-based indicator of long and middle distance running performance [30,31]. Based on our findings, CPET, with four minutes step duration, provides the potential for RE assessment implementation.

Estimating the magnitude of influence is of great practical relevance for the implementation of RE in routine diagnostics. It seems that subjects with efficient locomotion and subjects with substantially better age related aerobic fitness but less efficient locomotion are capable to reach comparable running speeds at RCP. Figure 1 illustrates that subjects with RE+ reached similar running speeds at RCP as athletes of the next higher categories, and therefore with higher aerobic fitness, throughout all performance levels. Despite a significantly lower mean $VO_{2max}$, the group Excellent/RE+ and the group Superior/RE- reached a comparable running speed ($V_{RCP}$). In conclusion, the impact of RE and $VO_{2max}$ on running speed ($V_{RCP}$) seems at least equivalent within this performance range. Contrary to this, the comparable speed between the groups Good and Excellent with RE+ can be explained partially by the similar $VO_{2max}$ values. The ACSM [20] uses Data on the basis of the Cooper Center Longitudinal Study to provide age and gender related percentile values for maximal aerobic capacity. It should be noted that due to the age and gender modulated interpretation, individual $VO_{2max}$ values within a category can differ substantially. Thus, the consideration of actual $VO_{2max}$ values is crucial for the interpretation of the presented results and might be a good approach for further investigations. The comparable range of RE values between categories provides preliminary evidence that RE rating, using reference values, could be applied throughout a broad range of aerobic performance levels. We applied median splits in order to generate a first basis for range based RE classification.

## Conclusions

Overall these results offer fairly convincing evidence that RE can be used as a sufficiently discriminating parameter of running performance in recreational athletes. Thus, determining RE gives useful data regarding the utilization of aerobic capacities in specific locomotion. With the applied procedure investigators may obtain all necessary data within a routine endurance performance diagnostics. Thus it generates valuable and valid information without additional costs and manageable effort. Therefore Running Economy seems to be not only “The Forgotten Factor in Elite Performance” [4] but also an underrated factor on recreational level. Further research should verify the influence and range of RE in runners of different performance levels. A valid categorization should be established for the assessment and interindividual comparison of RE values. Especially further investigations of modifiable factors affecting running economy may clarify its use for the implementation in training and assessment of recreational runners.

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# Manuskript II - Intensity related changes of running economy in recreational level distance runners

*Submission Type:* Original Investigation

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*Preferred running head:* Intensity related changes of running economy

# Manuskript II - Intensity related changes of running economy in recreational level distance runners


## Abstract:

***Background:*** Running economy (RE) is often described as a key demand of running performance. The variety of currently used methods with different running intensities and outcomes restricts interindividual comparability of RE in recreational runners. The purpose of this study was to compare the influence of RE, assessed as Oxygen cost (OC) and Caloric unit cost (CUC), on running speed at individual physiological thresholds.

***Methods:*** Eighteen recreational runners performed 1) A graded exercise test to estimate first ventilatory threshold (VT1), respiratory compensation point (RCP) and maximal oxygen uptake (VO2max), 2) Discontinuous RE assessment to determine relative OC in millilitres per kilogram per kilometre (ml/kg/km) and CUC in kilocalories per kilogram per kilometre (kcal/kg/km) at three different running intensities: VT1, RCP and at a third standardized reference point (TP) in between.

***Results:*** OC (ml/kg/km; at VT1:235.4±26.2; at TP:227.8±23.4; at RCP: 224.9±21.9) and CUC (kcal/kg/km at VT1:1.18±0.13; at TP:1.14±0.12; at RCP:1.13±0.11) decreased with increasing intensities ($p \leq .01$). Controlling for the influence of sex OC and CUC linearly correlated with running speed at RCP and VO2max ($p \leq .01$).

***Conclusions:*** Running Economy, even assessed at low intensity, is strongly related to running performance in recreational athletes. Both calculation methods used (OC and CUC) are sensitive for monitoring intensity related changes of substrate utilization. RE values decreased with higher running intensity indicating an increase of anaerobic- and subsequent decrease of aerobic substrate utilization.

## Introduction

Running specific economy of movement indicates the ability to transfer aerobic power into locomotion speed over ground. Hence, running economy (RE) is an approach to convert gross aerobic capacity into running performance output and it is mostly described as a primary physiological demand of endurance running performance [1,2]. A second physiological marker is the maximal rate of oxygen uptake ($VO_{2max}$). It represents an absolute criterion and key demand for aerobic energy metabolism [3]. Furthermore, endurance performance is strongly dependent on the ability to sustain a high percentage of $VO_{2max}$ ($\%VO_{2max}$) for the aspired event duration, which is a third physiological requirement [4]. In athletes with comparable $VO_{2max}$, both the ability to move economically and $\%VO_{2max}$ determine endurance running performance and therefore are essential for success [5,6]. While the relevance of all three key demands is widely accepted and performance diagnostics are available for recreational level distance runners, RE assessment so far is not carried out regularly on recreational level. Reasons comprise different factors: 1) A wide range of assessment approaches; 2) Lack of validation on recreational level or a recommended gold standard method; 3) The absence of valid rating systems or guideline values for evaluation; 4) Limited knowledge regarding factors affecting RE and the trainability of those; and therefore the resulting question whether the effort is worthwhile.

Assessment approaches differ in outcome parameters and test protocols. RE can be defined as oxygen cost (OC) [5] or caloric unit cost (CUC) [7] per defined distance travelled and can be scaled to body mass linearly (ml/kg/km, kcal/kg/km) [2] or with other allometric models ($ml/kg^{.75}/km$; $kcal/kg^{.75}/km$) [8]. While OC was predominantly used in previous studies, current works questioned the validity of this method and consequently recommended CUC as a more appropriate expression of RE, which furthermore is sensitive to changes in running speed [2, 7]. However, the question remains open, whether these findings and methods can be transferred to recreational level.

Currently, no validated rating scales for RE in recreational runners exist. Jones and colleagues created a scale for professionals and junior athletes based on OC with an average of 200ml/kg/km [9], but factors like anthropometric data or motor performance might lead to considerable differences in RE levels for recreational runners.

To allow a standardized application within a broad range of performance, RE could be assessed at comparable threshold intensities. However, reported opportunities and limitations of both current RE calculation methods (OC, CUC) within such an approach should be evaluated using a valid and applicable test protocol. The validity of body weight scaling methods that are based on high performance athletes has to be controlled. Furthermore, currently available rating systems that are based on competitive athletes as well should be evaluated for comparisons between recreational runners. The relation of RE to endurance running performance could be assessed in a laboratory setting via multiple benchmarks, such as running speed at respiratory compensation point (vRCP ), representing the highest steady state of aerobic energy metabolism, and running speed at maximal oxygen uptake ($vVO_{2max}$).

The purpose of this study was to evaluate a standardized approach to assess RE in recreational level runners and 1) to investigate intensity related changes of RE, assessed as oxygen cost (OC, ml/kg/km) and caloric unit cost (CUC, kcal/kg/km) and 2) to confirm the influence of RE on endurance running performance in recreational athletes.

## Materials and Methods

The study was approved by the local ethics committee (reference number 2014-89K) and adhered to the Declaration of Helsinki as well as the principles of good clinical practice. All subjects provided informed consent.

***Subjects:*** Central inclusion criterion was fulfilling criteria for minimal risk of exercise [10]. None of the subjects reported acute neuromuscular or musculoskeletal injuries at the time of the study. Seven female and eleven male recreational endurance runners (age: 24.1 ± 2.9 years, weight: 67.1 ± 7.5 kg, height: 175 ± 7.0 cm, BMI: 21.8 ± 1.7 kg/m$^2$) participated in the study. All subjects displayed regular levels of physical activity (307 ± 123min / week) including endurance running.

***Anthropometric data, maximal oxygen uptake and ventilatory thresholds:*** Anthropometric data was obtained prior to exercise on the first test day. Body mass in kilogram was measured using a digital scale to the nearest 0.1 kg, height in centimeter was determined to the nearest 1cm using a stadiometer and body mass index was calculated (BMI; kg/m$^2$). All subjects performed a graded exercise test (GXT) on an electronically driven treadmill (Quasar med, HP Cosmos, Wuerzburg, Germany) at 0° inclination. The GXT started with a resting reference phase. The initial running velocity was set individually at 6, 7 or 8 km/h based on participant reports about average training hours per week, running experience, preferred running speed and competition results. Speed was increased stepwise by 0.3 or 0.5 km/h, based on performance level, every 30 s until 18 km/h and hereafter inclination was increased 1 % every 30 s without further alterations of running velocity [11]. Test procedures were set individually to reach volitional exhaustion within 8-12min [12]. Participants were instructed to wear loose, breathable sportswear and their own running shoes. Participants were also asked to refrain from caffeine and vigorous physical activity for 24 h prior to testing procedures. Expired gases were measured using a breath-by-breath gas analyzer (Oxycon Mobile, Viasys Healthcare GmbH, Wuerzburg, Germany) for the determination of oxygen uptake ($VO_2$; ml·kg$^{-1}$) and carbon dioxide output ($VCO_2$; ml·kg$^{-1}$). Participants breathed through a rubber face mask (Hans Rudolph Inc., Shawnee, USA). The expired air was directed into a ventilation turbine and into the portable unit housing the $O_2$ and $CO_2$ gas analyzers. $VO_2$ and $VCO_2$ data were telemetrically transferred to a computer for further analysis. The measuring instrument was calibrated before each test using reference gases (outside air and 5% CO2, 16% O2) and automated standard ventilatory volumes (0.2 and 2.0 l/min). Sufficient reliability and validity of the

used indirect calorimetry device have been demonstrated [13,14]. Data was reduced to 5 s stationary averages.
The highest 30 s floating mean of $VO_2$ within testing time was defined as maximal oxygen uptake ($VO_{2max}$). Minimal running velocity which causes $VO_{2max}$ was defined as vVO2max. All subjects had to meet at least two of the following criteria for accepting values as maximal: 1) Respiratory Exchange Ratio (RER) above 1.15, 2) Attainment of maximum age-predicted heart rate (HR) +/- 5% [15], 3) Rate of perceived exertion via Borg-Scale ≥17 (17-20). First ventilatory threshold (VT1) and respiratory compensation point (RCP) were independently determined by two blinded investigators and differences were reviewed by a third person. First ventilatory threshold was defined as 1) Non-linear increase in $VCO_2$ vs. $VO_2$, 2) First non-linear increase of ventilation vs. workload ($V_E$/WL), 3) First increase of expiratory partial pressure of oxygen vs. workload ($P_{ET}O_2$/WL), 4) First non-linear increase of ventilatory equivalent of oxygen ($V_E/VO_2$) vs. workload with no concomitant increase of equivalent of carbon dioxide ($V_E/VCO_2$) [16]. Respiratory compensation point was identified by 1) Second non-linear increase in minute ventilation vs. workload ($V_E$/WL), 2) First non-linear increase of $V_E$ vs $VCO_2$ accompanied by a concomitant non-linear increase in $V_E/VCO_2$ vs. workload, 3) Non-linear decrease of expiratory partial pressure of carbon dioxide vs. workload ($P_{ET}CO_2$/WL) [16].
***Running economy:*** On a subsequent day, after at least 48h, participants RE was assessed. The subjects received the same instructions as for the GXT. After 5min at volitional speed below VT1 as a warm-up and familiarization period, the subjects ran 3 different submaximal speeds in the same order [7] for 6 min on a treadmill [17]. Running speed was set individually at 1) 90 % running speed of VT1 ($vVT1_{90}$), 2) Individuals arithmetic mean of speed at $VT1_{90}$ and $RCP_{90}$ (running speed at transition point, vTP), 3) At 90 % of RCP ($vRCP_{90}$). Subjects rested stationary on the treadmill for 5min between stages [7]. For the last 2 min of each stage 30 s averages of breath by breath $VO_2$ were calculated and steady state of oxygen uptake was defined as an increase < 100 ml $O_2$ between average values within this period [7]. RE was calculated as

absolute oxygen cost per kilometer (OC; ml/km) [5] using the 2 min average of $VO_2$. Caloric equivalent was determined via RER using average $VCO_2$ and $VO_2$ over the same time period and from this absolute caloric unit cost (CUC, kcal/km) was calculated [7,18,2]. The relations of body mass with absolute OC and CUC and ratio scaled values (value per kg[1]) were tested in order to validate the recently recommended method [2] in recreational runners. Based on a rating scale of Jones and colleagues [9] subjects were classified according to their ratio scaled OC (ml/kg/km) within the categories excellent (170-180), very good (180-190), above average (190-200), below average (200-210) and poor (210-220) [9]. Due to expected OC values the rating scale of was extended by adding the category "below poor" (>220 ml/kg/km).

***Statistical analyses:*** For statistical analysis, we used SPSS statistics software (IBM corp., Version 21.0) for Windows, Microsoft Excel 2010 and BIAS statistics software (Epsilon-Verlag, Version 10.05). Descriptive statistics are reported as mean and standard deviation. Due to sample size, Shapiro-Wilk normality test and Levene test for variance homogeneity were used. Potential differences in RE, RER and running speed (vRCP, $vVO_{2max}$) between males and females as well as differences of OC and CUC of running were assessed using ANOVA. In case of significance, post-hoc-tests using Bonferroni α-Error adjustment were applied. Partial correlation (SPSS), controlled for sex, was used to examine the relation of RE and running speed and to evaluate the influences of $VO_{2max}$, body mass and body mass index (BMI). Due to the pilot nature of this study no alpha-adjusting was applied for correlation analysis of RE and running speed. Statistical significance was set at $p < .05$.

## Results

All 18 participants completed both test procedures without interruptions. Graded exercise tests lasted 13:04 ± 1:24 min. No adverse events or medical conditions led to premature test termination. Means with standard deviation (SD) and individual data for $VO_{2max}$, VT1, RCP, $vVT1_{90}$, vTP and $vRCP_{90}$ as well as RE values (OC, CUC) including OC classification, for the latter three are presented in table 1. Steady state was confirmed for RE calculation of each subject at all running speeds.

*Table 1 (next page) - Individual values for running speed (v, km/h) and oxygen uptake (VO2, ml/kg/min) at VO2max (Maximal oxygen uptake), VT1 (First ventilatory threshold) and RCP (Respiratory compensation point). Running economy as oxygen cost (ml/kg/km) with rating via adjusted scale of Jones et al. (40) (bp below poor; p poor; ba below average; aa above average), and caloric cost (kcal/kg/km), running speed and oxygen uptake of vVT190 (90% speed of VT1), vTP (Speed of transition point), vRCP90.(90% speed of respiratory compensation point). Subjects are ranked for running speed of RCP (vRCP).*

| Subject | Sex | Body Mass | Body Mass Index | $vVO_{2max}$ | $VO_{2max}$ | vVT1 | %VO2 VT1 | vRCP | %VO2 RCP | $vVT1_{90}$ | %VO2 $vVT1_{90}$ | Oxygen Cost $vVT1_{90}$ | Caloric Cost $vVT1_{90}$ | vTP | %VO2 vTP | Oxygen Cost vTP (rating) | Caloric Cost vTP | vRCP 90 | %VO2 $vRCP_{90}$ | Oxygen Cost $vRCP_{90}$ | Caloric Cost $vRCP_{90}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 71,2 | 20,8 | 13,8 | 51,3 | 7,7 | 62,9 | 11,0 | 87,0 | 6,9 | 66,1 | 294,9 (bp) | 1,49 | 8,4 | 67,9 | 279,2 (bp) | 1,41 | 9,9 | 73,9 | 267,9 (bp) | 1,35 |
| 2 | 1 | 58,3 | 21,4 | 14,1 | 45,4 | 8,0 | 65,8 | 12,0 | 90,9 | 7,2 | 64,7 | 244,7 (bp) | 1,24 | 9,0 | 67,7 | 227,4 (bp) | 1,15 | 10,8 | 81,6 | 218,5 (p) | 1,10 |
| 3 | 2 | 71,4 | 22,8 | 15,7 | 56,8 | 8,4 | 64,3 | 12,1 | 83,5 | 7,6 | 62,3 | 279,1 (bp) | 1,39 | 9,3 | 67,2 | 258,4 (bp) | 1,29 | 10,9 | 77,4 | 253,0 (bp) | 1,27 |
| 4 | 2 | 71,6 | 22,3 | 15,5 | 52,6 | 10,2 | 68,0 | 12,2 | 84,8 | 9,2 | 73,2 | 250,9 (bp) | 1,27 | 10,1 | 68,0 | 243,0 (bp) | 1,23 | 11,0 | 76,2 | 240,4 (bp) | 1,21 |
| 5 | 1 | 59,6 | 20,9 | 13,8 | 44,0 | 9,0 | 69,3 | 12,3 | 91,2 | 8,1 | 63,7 | 207,9 (ba) | 1,04 | 9,6 | 72,6 | 204,5 (ba) | 1,02 | 11,1 | 80,9 | 204,2 (ba) | 1,02 |
| 6 | 1 | 61,7 | 20,9 | 15,5 | 49,6 | 9,6 | 63,2 | 12,6 | 84,0 | 8,6 | 61,9 | 214,3 (p) | 1,07 | 10,0 | 68,8 | 208,9 (ba) | 1,03 | 11,3 | 76,6 | 209,6 (ba) | 1,04 |
| 7 | 1 | 59,2 | 20,2 | 15,3 | 49,0 | 8,3 | 65,2 | 12,7 | 85,7 | 7,5 | 59,7 | 234,1 (bp) | 1,18 | 9,5 | 67,4 | 211,0 (p) | 1,07 | 11,4 | 82,4 | 202,6 (ba) | 1,02 |
| 8 | 2 | 66,2 | 21,4 | 17,0 | 63,6 | 10,0 | 64,1 | 12,8 | 81,7 | 9,0 | 61,1 | 259,2 (bp) | 1,31 | 10,3 | 63,2 | 256,8 (bp) | 1,30 | 11,5 | 73,1 | 262,1 (bp) | 1,32 |
| 9 | 2 | 74,3 | 20,8 | 14,6 | 53,5 | 9,9 | 66,9 | 12,9 | 87,4 | 8,9 | 68,5 | 247,2 (bp) | 1,24 | 10,3 | 73,0 | 251,2 (bp) | 1,27 | 11,6 | 81,0 | 248,0 (bp) | 1,25 |
| 10 | 2 | 72 | 23,8 | 15,3 | 50,3 | 11,0 | 76,0 | 13,3 | 87,5 | 9,9 | 75,9 | 231,1 (bp) | 1,17 | 11,1 | 73,3 | 236,0 (bp) | 1,19 | 12,0 | 80,1 | 221,5 (bp) | 1,12 |
| 11 | 2 | 63,5 | 20,7 | 17,0 | 55,7 | 10,6 | 67,5 | 13,3 | 83,5 | 9,5 | 66,0 | 232,2 (bp) | 1,17 | 10,8 | 67,5 | 215,7 (p) | 1,09 | 12,0 | 75,4 | 222,8 (bp) | 1,12 |
| 12 | 2 | 78,1 | 24,6 | 17,5 | 57,3 | 9,4 | 65,6 | 13,3 | 84,2 | 8,5 | 61,9 | 250,4 (bp) | 1,26 | 10,5 | 63,6 | 241,7 (bp) | 1,22 | 12,0 | 76,8 | 237,9 (bp) | 1,20 |
| 13 | 1 | 59 | 21,7 | 15,5 | 50,8 | 10,2 | 71,6 | 13,6 | 93,0 | 9,2 | 64,9 | 215,2 (p) | 1,06 | 10,7 | 74,3 | 228,3 (bp) | 1,13 | 12,2 | 86,2 | 224,6 (bp) | 1,13 |
| 14 | 1 | 74,4 | 22,2 | 14,8 | 48,5 | 10,4 | 72,7 | 14,1 | 98,4 | 9,4 | 66,3 | 205,3 (ba) | 1,03 | 11,1 | 77,4 | 205,8 (ba) | 1,04 | 12,7 | 89,9 | 206,1 (ba) | 1,04 |
| 15 | 1 | 52,4 | 19,0 | 16,1 | 50,3 | 9,9 | 64,6 | 14,6 | 88,3 | 8,9 | 58,7 | 198,9 (aa) | 1,00 | 11,0 | 70,9 | 193,4 (aa) | 0,98 | 13,1 | 82,5 | 196,3 (aa) | 0,99 |
| 16 | 2 | 76,7 | 25,9 | 18,8 | 56,3 | 10,0 | 66,2 | 16,1 | 90,7 | 9,0 | 64,4 | 242,0 (bp) | 1,22 | 11,8 | 73,5 | 219,8 (p) | 1,11 | 14,5 | 84,1 | 210,8 (p) | 1,06 |
| 17 | 2 | 73,1 | 21,8 | 19,6 | 54,4 | 12,2 | 70,5 | 16,7 | 90,2 | 11,0 | 69,0 | 204,5 (ba) | 1,03 | 13,0 | 74,9 | 202,4 (ba) | 1,02 | 15,0 | 83,3 | 200,6 (ba) | 1,01 |
| 18 | 2 | 64,4 | 21,0 | 22,1 | 67,4 | 10,0 | 51,4 | 17,8 | 89,9 | 9,0 | 49,9 | 224,4 (bp) | 1,11 | 12,5 | 64,1 | 217,6 (p) | 1,08 | 16,0 | 81,6 | 220,4 (bp) | 1,11 |
| Mean | | 67,1 | 21,8 | 16,2 | 53,2 | 9,7 | 66,4 | 13,5 | 87,9 | 8,7 | 64,3 | 235,4 | 1,18 | 10,5 | 69,7 | 227,8 | 1,14 | 12,2 | 80,2 | 224,9 | 1,13 |
| SD | | 7,5 | 1,7 | 2,2 | 5,8 | 1,1 | 5,2 | 1,8 | 4,2 | 1,0 | 5,7 | 26,2 | 0,13 | 1,2 | 4,2 | 23,4 | 0,12 | 1,6 | 4,4 | 21,9 | 0,11 |

Due to interaction effects of sex with OC ($F=7.62$; $p=.014$), CUC ($F=7.97$; $p=.012$) and $VO_{2max}$ ($F=15.27$; $p=.001$) but not with vRCP ($F=.6$; $p= .450$) or $vVO_{2max}$ ($F=4.25$; $p= .056$), partial correlations, controlled for sex, were calculated to assess the influence of RE (OC, CUC) at 3 different intensities ($vVT1_{90}$, vTP, $vRCP_{90}$), on submaximal- (vRCP) and maximal running speed ($vVO_{2max}$). RE values, as OC and CUC, at all intensities correlated with vRCP ($p< .01$) and $vVO_{2max}$ ($p< .01$). Oxygen- and caloric unit cost were highly interlinked at different speeds and within each other ($p< .001$).
RE data is displayed in figure 1. Oxygen cost differed significantly within the relative test speeds ($p< .01$). Post hoc tests revealed significantly higher oxygen cost at vVT1 in comparison to vTP and vRCP ($p< .01$). Caloric unit cost also differed significantly within test running speeds ($p< .01$). Similar to oxygen cost results, caloric unit costs were significantly higher for vVT1. Both costs of running thus decreased with increasing running intensity.

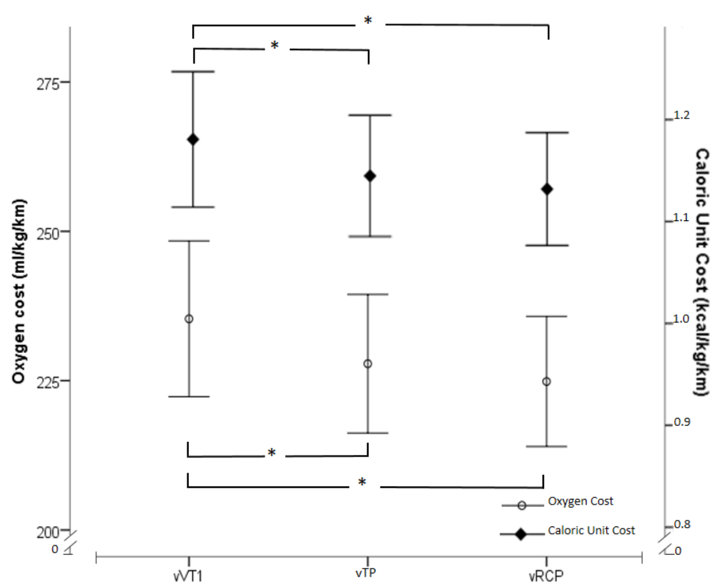


***Figure 1. –*** *Relative Oxygen Cost (OC) in millilitres and Caloric Unit Cost (CUC) in kilocalories, per kilogramm body mass per kilometre distance, of 90% running speed VT1 ($vVT1_{90}$), of transition point (vTP) and 90% running speed RCP ($vRCP_{90}$). Values are expressed as average ± 95% confidence intervals including significances (*p<.05)*

Linear and exponential regression models of gross RE values (OC, ml/km; CUC, kcal/km) with bodyweight (kg; $R^2$= .68; $R^2$= .72) or allometric scaled values (kg^.75; $R^2$= .68; $R^2$= .72) showed equivalent results. Plots of body mass against oxygen- and caloric unit cost are shown in Figure 2 and 3. Body mass or BMI neither correlates with linear scaled caloric unit cost (kcal/kg/km) nor with oxygen cost (ml/kg/km) of running.

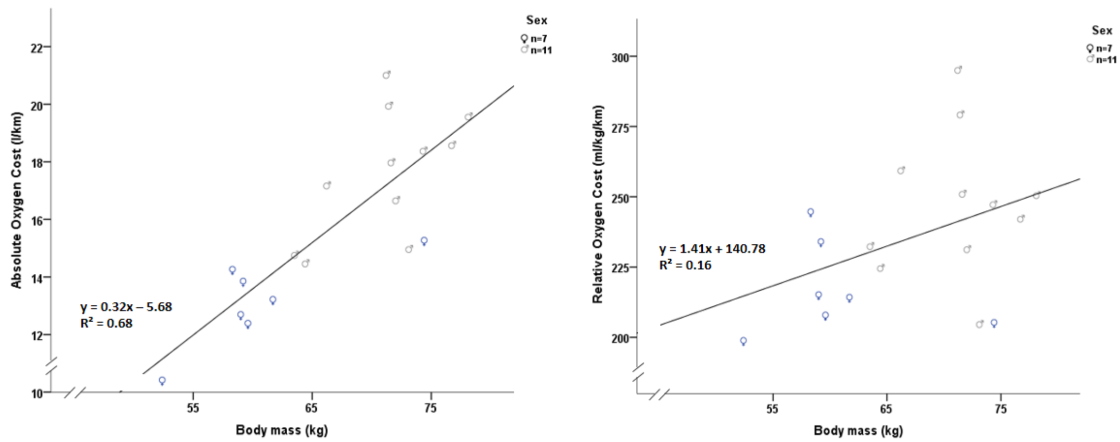


***Figure 2. –*** *Scatter plots of absolute Oxygen Cost (OC) in litres, and relative OC in milliliters per kilogram body mass, per kilometre distance, at 90 % running speed of VT1 ($vVT1_{90}$) against body mass, fitted with linear regression model (solid line).*

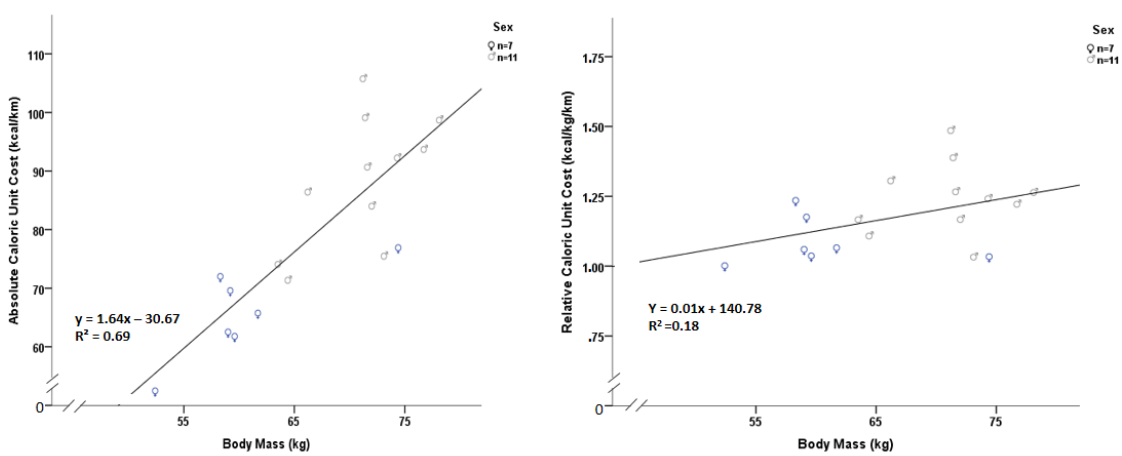


***Figure 3. –*** *Scatter plots of absolute Caloric Unit Cost (CUC) in kilocalories, and relative CUC in kilocalories per kilogram body mass, per kilometre distance at 90 % running speed of VT1 ($vVT1_{90}$) against body mass, fitted with linear regression model (solid line).*

Respiratory Exchange Ratio ($vVT1_{90}$: .99± .04; vTP: 1.00± .05; $vRCP_{90}$: 1.01± .05) increased significantly with test speed ($p< .001$), indicating an increase of anaerobic energy metabolism and changes of aerobic substrate proportions. Relative rates of oxygen uptake at VT1 and RCP (ml/kg/min) were significantly associated with relative $VO_{2max}$ ($p≤.01$). Maximal oxygen uptake and $VO_2$ at RCP showed a significant relationship to submaximal- (vRCP) and maximal running speed ($vVO_{2max}$) ($p≤.01$). RE- and $VO_{2max}$ values were not related ($p> .05$)

## Discussion

The present study yielded three main findings: 1) OC and CUC decreased from vVT1 to higher running speeds; 2) RE, assessed as OC and CUC, is associated with maximal- and running speed at the second ventilatory threshold; 3) Due to absence of significant relations of ratio scaled OC and CUC with body mass, linear ratio scaling seems to be a feasible method of accounting body mass in recreational distance runners. Our data confirm reported average values for recreational athletes [5,19]. Applying rating scales for younger high performance athletes, average OC for recreational runners at all intensities is rated below poor (>220 ml/kg/km). Therefore, the applicability of this rating scale [9] for OC classification in recreational athletes is limited.

This is the first study that assessed OC and CUC at two different, definable ventilatory threshold intensities (VT1, RCP). We observed decreasing OC and CUC with increasing exercise intensity. Significant correlations of RE to $vVO_{2max}$ and vRCP, which represents the highest steady state condition of aerobic energy metabolism, were found. Former studies used lactate threshold concepts to define a comparable relative intensity [20, 7, 2] or assessed maximal aerobic speed [8]. Others applied fix reference velocities, within a study sample of comparable aerobic performance [5]. Some groups used oxygen uptake per minute as indicator of RE [21] or compared RE at comparable rates of perceived exertion [22]. Our approach and some previous studies had in common to assess RE at comparable relative intensity, within a steady state of aerobic metabolism [7,5]. With this approach confirmed a relevant influence of RE on submaximal or maximal running speed. Our findings that both RE calculation techniques (OC, CUC) were sensitive for gross changes of substrate utilization and furthermore that RE values were significantly lower with increasing intensity contrast some recent findings. For example Helgerud et al. [8] did not state changes due to intensity, while Daniels and Daniels [23], reported increasing oxygen cost. In contrast Fletcher [7] and Shaw and colleagues [2], recently found increased CUC but not OC. Our study is the first analysis of RE in recreational runners providing evidence for decreasing OC and CUC values with higher intensities.

Due to the applied method [7,2], OC or CUC reflect aerobic energy metabolism per distance. Therefore, an incremental but indeterminable amount of anaerobic energy conversion has to be assumed with increasing exercise intensity. Consequently, a comparable relative intensity is critical for the comparison of individual RE values. During exercise at intensities below first ventilatory threshold (VT1), energy needs are satisfied by aerobic metabolism [24] and consequently respiratory exchange ratio is mainly determined by aerobic substrate mix. Resulting RE values (OC and CUC at $vVT1_{90}$) thus should reflect overall energy costs of running. Although velocity with attainment of VT1 is significantly lower than race pace, and therefore biomechanical and metabolic differences have to be considered, RE at VT1 ($VT1_{90}$) seems to be predictive for RE at higher intensities and a valid indicator for running performance.

Upon the point of VT1 an unknown increase of anaerobic energy metabolism must be considered and significantly lower RE values might therefore reflect this effect instead of a higher movement efficiency. Based on physiological aspects, the second ventilatory threshold or respiratory compensation point (RCP), reflecting the maximal steady state of energy metabolism, indicates the maximal intensity for RE assessment. However, some findings suggest RCP slightly overestimates maximal lactate steady state [16]. Therefore, exercise intensities below RCP might be the upper limit of valid OC and CUC determination.

Oxygen uptake, carbon dioxide exhalation, the resulting respiratory exchange ratio (RER) and therefore RE values, at intensities between VT1 and RCP, (55-80% of $VO_{2max}$ [16] ) are influenced by changes of aerobic substrate mix (fat and glucose) and the increasing amount of anaerobic glycolysis and subsequent bicarbonate buffering of occuring protons. Within this intensity range different metabolic combinations lead to comparable RER values, thus resulting calorimetric procedures are of limited significance [25]. The unknown individual aerobic substrate mix and amount of anaerobic energy conversion may result in a lack of differentiation between OC or CUC values. RER through combinations of bicarbonate buffering and aerobic substrate mix changes may therefore compromise the validity of CUC values at higher exercise intensities. Nevertheless our data support the relation between RE, of higher steady state intensities, and vRCP or $vVO_{2max}$.

Based on the currently available date, evidence for RE differences between females and males is inconclusive [23]. Therefore the consideration of performance and anthropometric differences is crucial. While some authors reported men with better oxygen cost of running, expressed as gross $VO_2$ at given test speeds [26], others found female middle distance runners to be more economical. Helgerud and colleagues (1994) compared male and female runners with comparable marathon performance (2h 40min) [27]. The group reported that performance matched male runners were heavier, had less body fat, higher $VO_{2max}$ and higher costs of running, which were furthermore independent of speed compared to females [27]. We found lower (more economical) OC and CUC of running, but also body mass and height, $VO_{2max}$ and $vVO_{2max}$, in recreational level women compared to men.

Some authors suggest a negative relationship between BM and ratio scaled RE [28,29], which would indicate an over-compensation of BM influence [2]. Consequently, many authors applied allometric scaling procedures, per kg^0.75 [8]. This procedure is based on the inverse relationship of body mass and $VO_{2max}$ for male (kg^81) and female athletes (kg^65) [27]. Others applied kg^0.66 [30]. Based on the methods described mostly without assessing validity for different subject populations. We adopted the method of Shaw and colleagues [2] and confirmed the validity of the applied method by verifying the influence of BM on ratio scaled RE values (ml/kg$^1$/km; kcal/kg$^1$/km). Several studies have demonstrated that running velocity with attainment of RCP [31–33] and $VO_{2max}$ [34–38] are valid laboratory-based indicators of long and middle distance running performance. Owing to the individual ambitions and race schedules of recreational runners, we were not able to collect valid competition-based indicators of performance (race splits, finish time or ranking), which had to be in close temporal relation to laboratory testing and with ideal, or at least comparable, external conditions. We chose to examine a heterogeneous group of runners. Therefore, experience, maximal performance, training schedules or anthropometric data showed a wide range. A ramp shaped protocol for optimal $VO_{2max}$ and ventilatory threshold determination, as gold standard procedures, was used [12]. Likewise with other studies RE testing took place on a separate date with fixed (increasing intensity) [23,7,2] instead of randomized sequence.

## Conclusions

Overall our results indicate that OC and CUC, assessed at low or high intensity could be used for RE assessment in recreational runners. Both calculation methods, OC and CUC, are sensitive for intensity related changes of substrate utilization but RE values decreased with higher running intensity. With respect to the physiological background we can not support the hypothesis of less overall energy costs of running at higher intensities. Lower RE values may be at least partly influenced by the increase of anaerobic- and subsequent decrease of aerobic substrate utilization, accompanied by changes of aerobic substrate mix and increased bicarbonate buffering. To control for these confounders and to assess overall RE based on oxygen uptake, the calculation of RE slightly below the first ventilatory (VT1) or “aerobic lactate” threshold might be advantageous. The interindividual comparison of RE at a similar intensity [7,5] directly related to a definable submaximal threshold is mandatory. We recommend the verification of applied BM scaling or, if appropriate, the calculation of an adequate model for allometric scaling [27]. Further studies should develop guideline values or rating scales for complementary RE assessment within performance diagnostics in recreational athletes.

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## Darstellung des eigenen Anteils an den einzelnen Manuskripten

Hiermit bestätige ich, dass ich Erstautor beider, dieser Dissertationsschrift zugrundeliegenden Publikationen bin. In Rücksprache mit allen aufgeführten Koautoren habe ich beide Manuskripte federführend erarbeitet und bei den genannten internationalen Publikationsorganen eingereicht. Die den Ergebnissen zugrundeliegenden statistischen Auswertungen habe ich ebenfalls in Rücksprache mit den Koautoren ausgewählt und durchgeführt. Ich war an allen Anteilen der Datenerhebung beteiligt.

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## Schriftliche Erklärung

Ich erkläre ehrenwörtlich, dass ich die dem Fachbereich Medizin der Johann Wolfgang Goethe-Universität Frankfurt am Main zur Promotionsprüfung eingereichte Dissertation mit dem Titel

Laufökonomie – Ein unterschätzter Faktor bei Amateursportlern?

in der Abteilung Sportmedizin unter Betreuung und Anleitung von Prof. Dr. Dr. Winfried Banzer ohne sonstige Hilfe selbst durchgeführt und bei der Abfassung der Arbeit keine anderen als die in der Dissertation angeführten Hilfsmittel benutzt habe. Darüber hinaus versichere ich, nicht die Hilfe einer kommerziellen Promotionsvermittlung in Anspruch genommen zu haben.

Die vorliegende Arbeit wurde bisher nicht als Dissertation eingereicht.

Vorliegende Ergebnisse der Arbeit wurden in folgendem Publikationsorgan veröffentlicht:

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