Effekte von Kompressionsbekleidung in Training und Wettkampf – Analyse zugrunde liegender physiologischer und biomechanischer Mechanismen

Inaugural-Dissertation
zur Erlangung der Doktorwürde der

Fakultät für Humanwissenschaften
der
Julius-Maximilians-Universität Würzburg

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Würzburg
2015

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Tag des Kolloquiums: 06. November 2015

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Abkürzungsverzeichnis

Abkürzung	Erklärung
AMV [$L \cdot min^{-1}$]	Atemminutenvolumen
d	Effektstärke nach Cohen
ES	Effektstärke
EMG	Elektromyographie
GPS	Global Positioning System
HF [$s \cdot min^{-1}$]	Herzfrequenz
La^-	Blutlaktat
m	Meter
min	Minute
mmHg	Millimeter-Quecksilbersäule (Druckeinheit)
NIRS	Nahinfrarotspektroskopie
P	Statistisches Signifikanzniveau
PET	Positronen-Emissions-Tomographie
pO_2 [mmHg]	Sauerstoffpartialdruck
RPE	Subjektives Belastungsempfinden (Ratings of perceived exertion)
s	Sekunden
SO_2 [%]	Sauerstoffsättigung
VO_2 [$mL \cdot min^{-1}$]	Sauerstoffaufnahme
VO_{2peak} [$mL \cdot kg^{-1} \cdot min^{-1}$]	Maximale Sauerstoffaufnahme
W	Watt

Abbildungsverzeichnis

I. Studienverzeichnis

1. Born DP, Sperlich B, Holmberg HC. (2013). **Bringing light into the dark: effects of compression clothing on performance and recovery.** *Int J Sports Physiol Perform*, 8(1), 4-18.

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2. Born DP, Zinner C, Herlitz B, Richter K, Holmberg HC, Sperlich B. (2014). **Muscle Oxygenation Asymmetry in Ice Speed Skaters is not Compensated by Compression.** *Int J Sports Physiol Perform*, 9(1), 58-67.

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3. Born DP, Holmberg HC, Goernert F, Sperlich B. (2014). **A novel compression garment with adhesive silicone stripes improves repeated sprint performance – a multi-experimental approach on the underlying mechanisms.** *BMC Sports Sci Med Rehabil*, May 30(6), 21.

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II. Kurzzusammenfassung

Einleitung: Es konnte gezeigt werden, dass die Applikation von Kompressionsbekleidung zu einem erhöhten Blutfluss bei Patienten mit venöser Insuffizienz führt und das Thromboserisiko bei bettlägerigen und postoperativen Patienten reduziert. Davon ausgehend, dass Kompressionsbekleidung auch bei gesunden und trainierten Athlet/innen zu einer verbesserten Hämdynamik führt, wurde eine Vielzahl an Studien durchgeführt, die nach einer Leistungssteigerung durch das Tragen von Kompressionsbekleidung während sportlicher Belastung gesucht haben. Die Ergebnisse der bisher veröffentlichten Studien widersprechen sich jedoch häufig und lassen kein abschließendes Fazit bezüglich ergogener Effekte von Kompressionsbekleidung auf die Leistung während körperlicher Belastung zu. Auch ist unklar, welche physiologischen und/oder biomechanischen Mechanismen bei gesunden und trainierten Athlet/innen zu einer potentiellen Leistungssteigerung führen könnten.

Ziel der vorliegenden Arbeit war es daher: 1) Belastungsarten und –intensitäten zu identifizieren, bei denen das Tragen von Kompressionsbekleidung leistungssteigernde Effekte verspricht, 2) die identifizierten Potentiale anhand empirischer Datenerhebung zu evaluieren und 3) die physiologischen und biomechanischen Mechanismen zu untersuchen, die einer möglichen Leistungssteigerung mit Kompressionsbekleidung bei gesunden und trainierten Athlet/innen zugrunde liegen könnten.

Methodik: Mittels eines Übersichtsartikels und Berechnung von Effektstärken wurden verschiedene Belastungsarten und -intensitäten identifiziert, bei denen das Tragen von Kompressionsbekleidung leistungssteigernde Effekte verspricht (*Studie 1*). Auch

wurden die möglichen Mechanismen zusammengetragen, die einer Leistungssteigerung zugrunde liegen könnten. Basierend auf diesen Ergebnissen wurden die Untersuchungsprotokolle für die weiteren Studien entwickelt.

In *Studie 2* absolvierten hoch-trainierte Eisschnellläufer/innen eine 3000 m Wettkampfsimulation mit und ohne Kompressionsbekleidung in randomisierter Reihenfolge. Physiologische Daten wurden mittels mobiler Spirometrie und Nahinfrarotspektroskopie (NIRS) erhoben.

Des Weiteren wurden Athletinnen aus Mannschaftssport und Leichtathletik einer intermittierenden Sprintbelastung mit dreißig 30 m Sprints und einer Abgangszeit von einer Minute mit und ohne Kompressionsbekleidung in randomisierter Reihenfolge unterzogen (*Studie 3*). Neben mobiler Spirometrie und NIRS wurden biomechanische Daten mittels kinematischer Bewegungsanalyse und Elektromyographie erhoben.

Ergebnisse:*Studie 1* zeigte ein leistungssteigerndes Potential mit der Applikation von Kompressionsbekleidung bei hoch-intensiver und weniger bei submaximaler Belastungsintensität. Insbesondere hoch-intensive Ausdauer- (> 3 Minuten), Sprint- und Sprungbelastung als auch die Erholungsfähigkeit von Kraft- und Schnellkraft scheinen durch Kompressionsbekleidung verbessert. Die Ergebnisse zeigen auch, dass bisher nur wenige Daten bei weiblichen Sportlern erhoben wurden. Auch evaluierten nur wenige Studien die Effekte von Kompressionsbekleidung bei Athlet/innen auf höchstem Leistungsniveau.

In *Studie 2* zeigte die Applikation von Kompressionsbekleidung während der 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen keinen Effekt auf die Laufleistung. Auch blieben mittels NIRS gemessenes Blutvolumen und

Muskeloxygenierung im *m. quadrizeps femoris* sowie alle weiteren kardio-respiratorischen, metabolischen und subjektiven Parameter unbeeinflusst.

Dagegen war die Laufleistung während eines intermittierenden (30 x 30 m) Sprintprotokolls mit Kompressionsbekleidung signifikant verbessert (*Studie 3*). Auch in dieser Untersuchung blieben alle gemessenen hämodynamischen, kardio-respiratorischen und metabolischen Parameter unbeeinflusst. Die kinematische Bewegungsanalyse zeigte jedoch, dass Kompressionsbekleidung zu veränderter Lauftechnik führt und die Schrittlänge bei gleichbleibender Schrittfrequenz vergrößert. Auch wurde die Sprintbelastung lokal an der Oberschenkelmuskulatur subjektiv weniger anstrengend empfunden.

Zusammenfassung und Fazit: Die Applikation von Kompressionsbekleidung zeigte keine generelle leistungssteigernde Wirkung während körperlicher Belastung bei gesunden und trainierten Athlet/innen. Abhängig von Belastungsart und –intensität manifestieren sich ergogene Effekte während hoch-intensiver Lauf- insbesondere intermittierender Sprintbelastungen. Im Zusammenhang mit weiteren Untersuchungen scheinen die ergogenen Effekte jedoch nicht auf veränderter Hämodynamik zu basieren. Der blutflusssteigernde Effekt von Kompressionsbekleidung, der in klinischen Studien bei Patienten mit venöser Insuffizienz gezeigt wurde, lässt sich nicht in gleichem Maße bei gesunden und trainierten Athlet/innen nachweisen. Vielmehr scheinen kinematische und subjektive Parameter, wie eine veränderte Lauftechnik und verringertes Belastungsempfinden, die intermittierende Sprintleistung verbessert zu haben.

III. Abstract

Introduction: Compression clothing has been shown to improve blood flow in patients suffering from insufficient venous valves. Assuming that the hemodynamics may be improved with compression clothing in healthy and trained individuals as well, many studies have evaluated the effect of compression clothing during various types of exercise. However, previous research has reported conflicting results and it remains unclear whether compression clothing has any performance enhancing effects. Therefore, the aim of the thesis was to 1) identify types and intensities of exercise that might benefit by the application of compression clothing, 2) provide evidence-based data on possible performance enhancing effects and 3) evaluate and explain the underlying physiological and biomechanical mechanisms associated with the application of compression clothing in healthy and trained individuals.

Methods: To identify the potential types and intensities of exercise that might benefit by the application of compression clothing, a literature review and an effect size calculation analysis were performed (*Study 1*). As well, the potential physiological and biomechanical mechanisms that possibly could lead to an improved exercise performance in healthy and trained individuals were summarized from the literature.

In *Study 2*, elite ice speed skaters performed a 3000 m race simulation with and without compression clothing in a randomized order. Cardio-respiratory, hemodynamic and metabolic data were measured using a portable gas analyzer and a wireless near-infrared spectroscopy device.

In *Study 3*, athletes from team sports and track-and-field performed a repeated sprint protocol consisting of thirty 30 m sprints (one sprint initiated every minute) with and

without compression clothing in a randomized order. Additional to the physiological data, video analysis and electromyography were used to evaluate running technique and neuro-muscular effects with the application of compression clothing.

Results: *Study 1* revealed a possible ergogenic effect of compression clothing during high-intensity rather than submaximal exercise. A practical meaningfulness to apply compression clothing was shown for high-intensity endurance exercise such as time-to-exhaustion and time trial performance (> 3 min), repeated sprinting and jumping as well as recovery of muscular strength and power. *Study 1* showed that more research is necessary to understand the effects of compression clothing in females, and well-trained or elite athletes. Additionally, the mechanisms underlying possible ergogenic effects of compression clothing in healthy and trained individuals need to be investigated.

Based on the results of *Study 1*, the exercise protocols for *Study 2* and *3* were designed. *Study 2* showed, that there were no performance benefits when applying compression clothing during a 3000 m race simulation in elite ice speed skaters. None of the measured cardio-respiratory, hemodynamic, metabolic or subjective parameters were affected. In contrast, the application of compression clothing improved the repeated sprint performance (30 x 30 m) in *Study 3*. All measured cardio-respiratory, hemodynamic, and metabolic parameters remained unaffected. Kinematic data however revealed that there was an altered running technique with increased step length but unchanged step frequency. Perceived exertion was reduced in upper leg muscles with compression clothing.

Conclusion: There is no overall performance boosting effect with the application of compression clothing. Performance seems to be improved during high-intensity exercise, especially repeated sprinting, rather than prolonged and submaximal exercise protocols. Unlike in patients suffering from insufficient venous valves, in healthy and trained individuals the application of compression clothing does not seem to alter hemodynamics or enhance blood flow. Rather, biomechanical and subjective data, such as altered running technique and reduced perceived exertion, seemed to improve repeated sprint performance.

1. Einleitung

Es konnte gezeigt werden, dass die Applikation von Kompressionsbekleidung zu einem erhöhten Blutfluss bei Patienten mit venöser Insuffizienz führt (Agu, Baker et al. 2004) und das Thromboserisiko bei bettlägerigen und postoperativen Patienten reduziert (Agu, Hamilton et al. 1999). Auch bei Langstreckenflügen verringerte das Tragen von komprimierenden Textilien durch Inaktivität und hypobare Hypoxie induzierte Ödeme, Muskelschwellung und -schmerz (Hagan & Lambert 2008). Zurück geht dies auf eine durch die Kompressionsbekleidung veränderte Hämodynamik mit verbesserter Muskelpumpfunktion, gesteigertem venösen Blutrückfluss (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976) und erhöhter Muskeloxygenierung (Agu, Baker et al. 2004).

Um in aufrechter Körperhaltung einen Rücktransport des Blutes von den unteren Extremitäten zum Herzen entgegen die gravitationsbedingte hydrostatische Drucksäule von 80–100 mmHg zu ermöglichen, befinden sich im venösen System in regelmäßigen Abständen sogenannte Venenklappen (McArdle, Katch et al. 2009). Kontrahieren die ein Venengefäß umgebenden Muskel, drücken sie die elastische Venenwand zusammen und das Blut fließt, durch die Ventilfunktion der unidirektionalen Venenklappen, in Richtung des Herzens (McArdle, Katch et al. 2009). Die Applikation von Kompressionsbekleidung führt zu einer verstärkten Überlappung der Venenklappen und Umverteilung des Blutes vom oberflächlichen in das tiefere Venensystem (Lawrence & Kakkar 1980). So erhöht die gesteigerte Effizienz der Muskelpumpfunktion den venösen Blutrückfluss (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lewis, Antoine et al. 1976).

Unter der Annahme, dass sich dieser Mechanismus gleichermaßen bei gesunden und trainierten Athlet/innen zeigt, wurden in den vergangenen Jahren eine Vielzahl an Studien durchgeführt, die während körperlicher Belastung eine mögliche Steigerung von Blutfluss und damit der Ausdauerleistung mit Kompressionsbekleidung untersucht haben. Während hoch-intensiver Laufbelastung konnte mit der Applikation von Kompressionsbekleidung tatsächlich eine mittels Nahinfrarotspektroskopie (NIRS) gemessene Steigerung des Blutvolumens im *m. quadrizeps femoris* festgestellt werden (Dascombe, Hoare et al. 2011). Widersprüchlich erscheint, dass die Kompressionsbekleidung in der selbigen Studie die Muskeloxygenierung reduzierte (Dascombe, Hoare et al. 2011). Andere Studien zeigten eine erhöhte Muskeloxygenierung bei hoch-intensiver Belastung mit der Applikation von Kompressionsbekleidung, jedoch blieb das mittels NIRS gemessene Blutvolumen unverändert (Scanlan, Dascombe et al. 2008; Sear, Hoare et al. 2010). Es bleibt unklar, ob die Applikation von Kompressionsbekleidung bei gesunden und trainierten Athlet/innen zu einer verbesserten Hämodynamik und damit gesteigerter Leistung während körperlicher Belastung führt.

Auch ist unklar, ob die Applikation von Kompressionsbekleidung zu veränderten metabolischen Parametern führt. Einige Studien zeigten eine verringerte Blutlaktatkonzentration mit Kompressionsbekleidung und gehen davon aus, dass ein gesteigerter Blutfluss zu vermehrtem Abtransport von Laktatmolekülen und anschließender Verstoffwechslung in anderen Geweben führt (Berry & McMurray 1987; Chatard, Atlaoui et al. 2004; Sperlich, Born et al. 2013c). Allerdings zeigten andere Studien keine Veränderung der Blutlaktatkonzentration während submaximaler (Ali, Creasy et al. 2010; Sperlich, Haegele et al. 2011) oder nach hoch-intensiver Belastung (Duffield, Cannon et al. 2010; Duffield & Portus 2007; Sperlich, Haegele et al. 2010). Eine Studie konnte sogar erhöhte Blutlaktatkonzentration mit Kompressionsbekleidung nach hoch-intensiver Belastung feststellen (Rimaud, Messonnier et al. 2010).

Uneinheitlich sind auch die Ergebnisse bezüglich einer mit Kompressionsbekleidung veränderten Sauerstoffaufnahme. Eine frühe Studie zeigte eine signifikant reduzierte Sauerstoffaufnahme während submaximaler Laufbelastung (Bringard, Perrey et al. 2006). Spätere Untersuchungen konnten diesen Effekt jedoch während submaximaler (Ali, Creasy et al. 2010; Sperlich, Haegele et al. 2011) als auch hoch-intensiver Belastungsintensität nicht bestätigen (Sperlich, Born et al. 2013b; Sperlich, Born et al. 2013c; Sperlich, Haegele et al. 2010). Eine Studie zeigte sogar eine erhöhte Sauerstoffaufnahme mit Kompressionsbekleidung während hoch-intensiver Laufbelastung (Dascombe, Hoare et al. 2011).

Auch bei einer möglichen Steigerung der Leistung während körperlicher Belastung zeigte sich eine heterogene Ergebnislage mit der Applikation von Kompressionsbekleidung während verschiedener Belastungsarten und –protokolle. Während Kompressionsbekleidung die Zeit bis zur Ermüdung bei einem stufenförmigen Belastungsprotokoll signifikant verlängerte (Kemmler, von Stengel et al. 2009), konnten weitere Studien eine Leistungssteigerung bei stufenförmigen Belastungsprotokollen (Dascombe, Hoare et al. 2011; Sperlich, Haegele et al. 2010) oder während 10 km Wettkampfsimulationen nicht bestätigen (Ali, Caine et al. 2007; Ali, Creasy et al. 2011). Die Ergebnisse mehrerer Studien deuten jedoch mit hohen Effektstärken darauf hin, dass Kompressionsbekleidung bei intermittierender, hoch-intensiver Lauf- und/oder Sprintbelastung zu gesteigerter Laufleistung führen könnte (Goh, Laursen et al. 2010; Higgins, Naughton et al. 2009; Sear, Hoare et al. 2010).

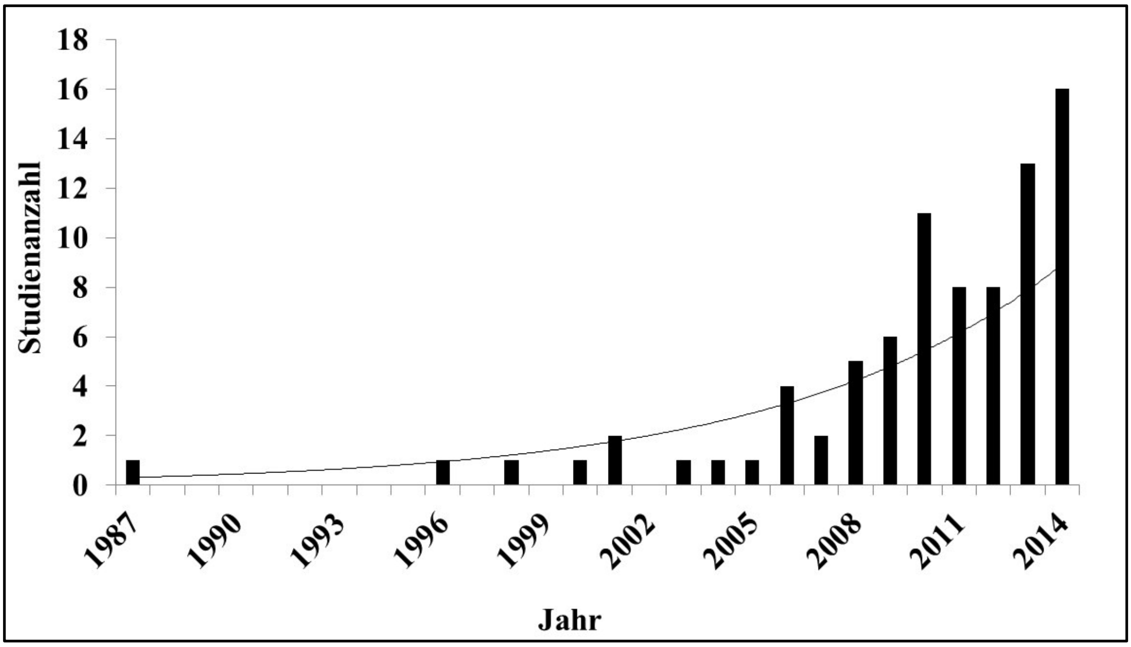

Abb. 1: Exponentieller Anstieg der jährlich veröffentlichten Untersuchungen von Kompressionsbekleidung während körperlicher Belastung bei gesunden und trainierten Athlet/innen.

Aufgrund der widersprüchlichen Ergebnisse lässt sich trotz der Vielzahl an Studien, die die Effekte von Kompressionsbekleidung bei gesunden und trainierten Athlet/innen in den vergangen Jahrzehnten untersucht haben (siehe Abb. 1), kein abschließendes Fazit bezüglich möglicher leistungssteigernder Effekte von Kompressionsbekleidung in Training und Wettkampf ziehen.

Ziel der vorliegenden Arbeit war es daher, eine umfassende und wissenschaftlich basierte Bewertung möglicher leistungssteigernder Effekte von Kompressionsbekleidung während körperlicher Belastung bei gesunden und trainierten Athlet/innen vorzunehmen. Potentielle Effekte von Kompressionsbekleidung, während verschiedener Belastungsarten und –intensitäten, wurden in *Studie 1* anhand eines Übersichtsartikels und Berechnung von Effektstärken erfasst. Basierend auf diesen Ergebnissen wurden die Untersuchungsdesigns für *Studie 2 und 3* konzipiert und die identifizierten Potentiale anhand von Labor- und

Felduntersuchungen evaluiert. Eine umfassende Datenerhebung hämodynamischer, kardio-respiratorischer, metabolischer und neuro-muskulärer Parameter wurde in die Studiendesigns implementiert, um die einer potentiellen Leistungssteigerung zugrunde liegenden physiologischen und biomechanischen Mechanismen eingehend zu untersuchen.

Der Aufbau der Arbeit gliedert sich in eine prägnante Zusammenfassung der Methodik und Ergebnisse von *Studien 1 - 3*. Im Anschluss werden die Ergebnisse in ihrem Gesamtkontext diskutiert, um ein abschließendes Fazit zu einer möglichen Leistungssteigerung mit Kompressionsbekleidung und den zugrunde liegenden physiologischen und biomechanischen Mechanismen bei gesunden und trainierten Athlet/innen in Training und Wettkampf zu ziehen.

2. Methodik- und Ergebnisdarstellung

2.1. ***Studie 1*****:** Born DP, Sperlich B, Holmberg HC. (2013). **Bringing light into the dark: effects of compression clothing on performance and recovery.** *Int J Sports Physiol Perform*, 8(1), 4-18.

International Journal of Sports Physiology and Performance, 2013, 8, 4-18

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BRIEF REVIEW

Bringing Light Into the Dark: Effects of Compression Clothing on Performance and Recovery

Dennis-Peter Born, Billy Sperlich, and Hans-Christer Holmberg

2.1.1 Untersuchungsdesign von Studie 1

Zur Erfassung potentieller Effekte von Kompressionsbekleidung während verschiedener Belastungsarten und -intensitäten wurde ein Übersichtsartikel mit meta-analytischem Ansatz erstellt. Mittels einer Literaturrecherche in den medizinischen Datenbanken PubMed, MEDLINE, SPORTDiscus und Web of Science wurden 423 potentielle Studien erfasst (siehe Abb. 2).

Festgelegt wurden als Kriterien für den Einschluss der Studien in die Effektstärkenberechnung, dass 1) Kompressionsbekleidung während und/oder nach körperlicher Belastung mit sportspezifischem Hintergrund untersucht, 2) physiologische, biomechanische und/oder psychologische Parameter zur Erklärung zugrunde liegender Mechanismen erhoben, 3) eine Intervention mit Kompressionsbekleidung einer Kontrollbedingung ohne komprimierende Textilien gegenüber gestellt, 4) die Ergebnisse in absoluten Werten (Mittelwert ± Standardabweichung) für die anschließende Effektstärkenberechnung angegeben, 5) nur gesunde Probanden ohne jegliche kardiovaskuläre, metabolische oder muskuloskeletale Dysfunktion eingeschlossen und 6) die Studien in einschlägigen Fachzeitschriften mit Gutachterverfahren veröffentlicht wurden.

Wegen Nichterfüllung der Einschlusskriterien wurden 379 der ursprünglich 423 gesichteten Studien nach eingehender Begutachtung der Abstracts ausgeschlossen. Die verbleibenden 44 Studien wurden einer genauen Betrachtung der Methodik im Volltext unterzogen, woraufhin sechs weitere Studien die Einschlusskriterien nicht erfüllten. Von den verbleibenden 38 Studien wurden sieben ausgeschlossen, da die Ergebnisse ohne absolute Werte (Mittelwert ± Standardabweichung) angegeben waren und somit keine Berechnung der Effektstärken möglich war. Letztlich wurde aus 31 Studien die Effektstärke *g* anhand von Mittelwert, Standardabweichung und Stichprobengröße nach Hedges und Olkin (1985) berechnet. Bewertet wurden die Effektstärken nach einer von Fröhlich und Mitarbeitern (2009) für die trainingswissenschaftliche Praxis vorgeschlagenen Definition, wonach eine Effektstärke < 0,10 als trivialer, 0,10 – 0,30 als kleiner, 0,30 – 0,50 als mittlerer und > 0,50 als großer Effekt einzustufen ist.

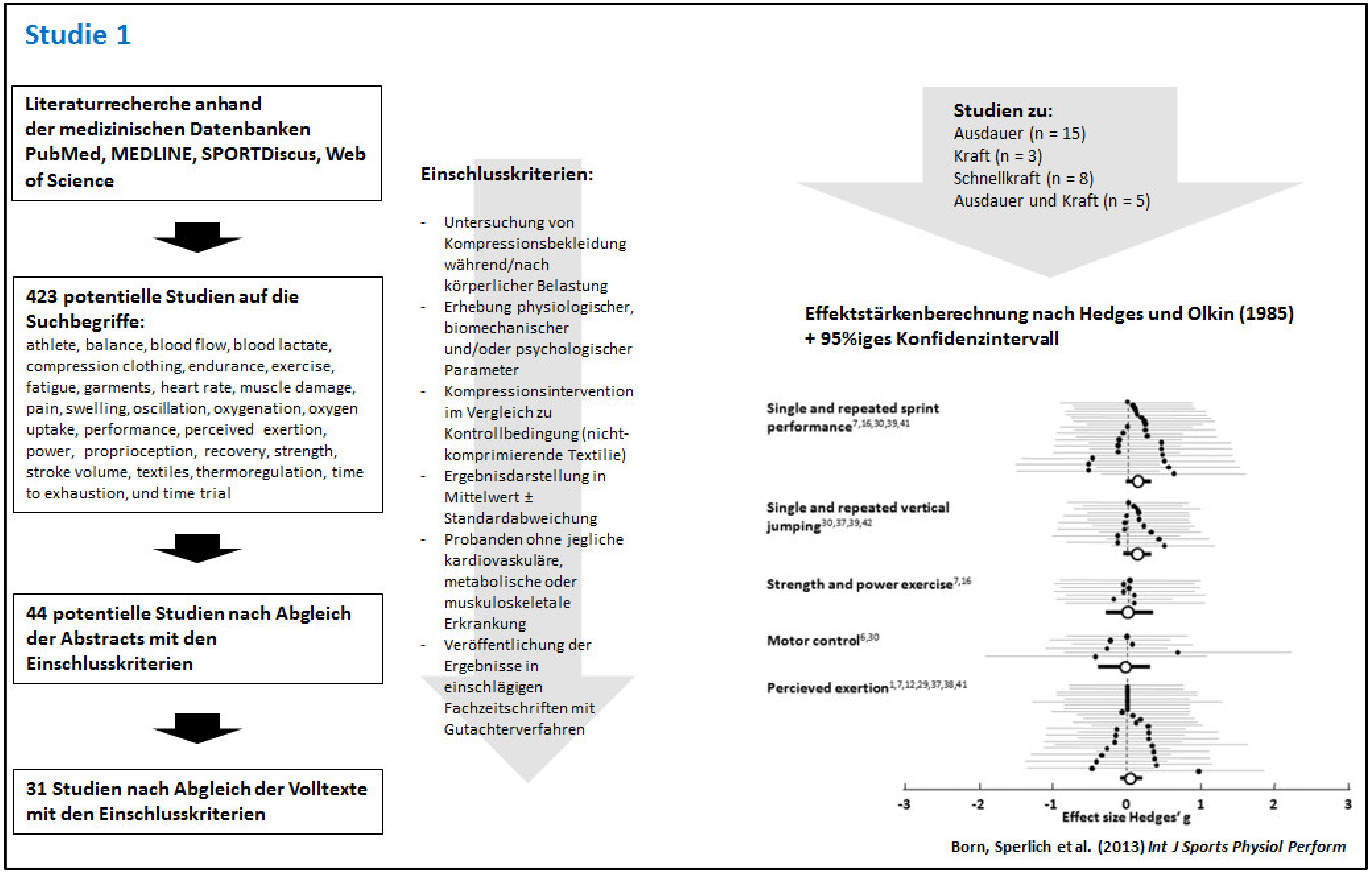

Abb. 2: Untersuchungsdesign von *Studie 1* (übersetzt und modifiziert aus Born, Sperlich et al. 2013, *Int J Sports Physiol Perform*, 8(1), 4-18).

2.1.2 Zusammenfassung der Ergebnisse von Studie 1

Die Ergebnisse von *Studie 1* zeigten eine hohe Variabilität bei der verwendeten Kompressionsfläche bisheriger Untersuchungen (Kompressionsshirts n = 2, knielange Kompressionsstrümpfe n = 9, hüfthohe Kompressionsstrümpfe n = 2, Kompressionshosen n = 14, knielange Kompressionshosen n = 3 und Anzüge mit Ganzkörperkompression n = 4). Auch die Druckstärke der Kompressionsbekleidung variierte in hohem Maße und reichte von 8 bis 40 mmHg. Primär wurden männliche Athleten als Versuchspersonen in den Studien untersucht (♀ = 3, ♂ = 22, ♀ & ♂ = 5, ohne Angabe = 1). Der Leistungsstand der Probanden wurde bei lediglich acht Studien als gut-trainiert eingestuft und in nur drei Studien zeigten die Probanden Merkmale eines elitären Leistungsniveaus. Zwanzig Studien integrierten Probanden mit niedrigem Leistungsniveau.

Anhand der Effektstärken (ES) konnte die Applikation von Kompressionsbekleidung als praktisch Relevant eingestuft werden für 1) hoch-intensive Ausdauerbelastung (3 – 60 min; ES = 0,15), 2) isolierte und wiederholte Sprintbelastung (10 – 60 m; ES = 0,12), 3) isolierte und wiederholte Sprungbelastung (ES = 0,10), 4) die Erholungsfähigkeit von Kraft- und Schnellkraft (höchste ES = 0,13), 5) Reduktion der Blutlaktatkonzentration nach hoch-intensiver Belastung (ES = 0,20), 6) Reduktion von Muskelschwellung (ES = 0,35) und -schmerz (ES = 0,47) nach hoch-intensiver Belastung und 7) Erhöhung der Körpertemperatur (ES = 1,38).

Keine Veränderung zeigten 1) gering komplexe Kraftbelastungen (ES = 0,00), 2) koordinative Aufgaben (ES = -0,02), 3) das subjektive Belastungsempfinden (ES = 0,05), maximale (ES = 0,08) und submaximale Sauerstoffaufnahme (ES = 0,01), 4) Blutlaktatkonzentration während kontinuierlicher Belastung (ES = -0,04),

5) Blutgase (SO_2, pO_2, Plasma pH; höchste ES = 0,02) und 6) kardiale Parameter wie Herzfrequenz (ES = 0,07), Schlagvolumen und Herzminutenvolumen (ES = -0,08). Die Verringerung myozellulärer Proteine (niedrigste ES = -0,10) und die Erholung der Sprintfähigkeit (ES = -0,13) zeigten einen negativen Effekt mit der Applikation von Kompressionsbekleidung.

Zusammenfassend zeigte *Studie 1* eine praktische Relevanz für die Applikation von Kompressionsbekleidung bei hoch-intensiver Ausdauer- (> 3 Minuten), Sprint- und Sprungbelastung als auch der Erholungsfähigkeit von Kraft- und Schnellkraft. Damit manifestierte sich das leistungssteigende Potential von Kompressionsbekleidung bei hoch-intensiver und weniger submaximaler Belastungsintensität. Ein Forschungsdefizit zeigte sich bei Athlet/innen auf hohem Leistungsniveau und insbesondere bei weiblichen Sportlern.

In *Studie 1* wurde eine Vielzahl potentieller hämodynamischer, vaskulärer, kardio-pulmonaler, metabolischer und neuro-muskulärer Mechanismen diskutiert, die mit der Applikation von Kompressionsbekleidung bei gesunden und trainierten Athlet/innen zu einer Leistungssteigerung führen könnten. An dieser Stelle bleibt zu evaluieren, ob sich die bei bettlägerig, postoperativ und venös insuffizienten Patienten gezeigte Blutflusssteigerung mit der Applikation von Kompressionsbekleidung auch bei gesunden und trainierten Athlet/innen nachweisen lässt.

2.2. *Studie 2*: Born DP, Zinner C, Herlitz B, Richter K, Holmberg HC, Sperlich B. (2014). **Muscle Oxygenation Asymmetry in Ice Speed Skaters is not Compensated by Compression.** *Int J Sports Physiol Perform*, 9(1), 58-67.

International Journal of Sports Physiology and Performance, 2014, 9, 58-67
http://dx.doi.org/10.1123/IJSPP.2012-0210

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ORIGINAL INVESTIGATION

Muscle Oxygenation Asymmetry in Ice Speed Skaters: Not Compensated by Compression

Dennis-Peter Born, Christoph Zinner, Britta Herlitz, Katharina Richter, Hans-Christer Holmberg, and Billy Sperlich

Im Eisschnelllauf bewegen sich die Athlet/innen mit Spitzengeschwindigkeiten > 45 $km \cdot h^{-1}$ auf der Eisbahn. In den langezogenen Kurven führen die hohen Zentrifugalkräfte und langen Gleitphasen zu anhaltender isometrischer Muskelspannung (de Boer, Ettema et al. 1987; Kandou, Houtman et al. 1987) und substantieller Reduktion des Blutflusses im *m. quadrizeps femoris* (Foster, Rundell et al. 1999; Hesford, Laing et al. 2012). Zur Optimierung der Aerodynamik und um bei jedem Schritt einen maximalen Abdruck zu gewährleisten, nehmen Eisschnellläufer/innen eine tief gebeugte Körperhaltung ein (de Koning, Foster et al. 2005). Dadurch kommt es auch auf den geraden Abschnitten der Eisbahn zu hoher isometrischer Muskelspannung, Blutflussrestriktion (Foster, Rundell et al. 1999; Rundell, Nioka et al. 1997), einem hohen Anteil anaerober Energiebereitstellung und hoher Blutlaktatkonzentration (Foster, Rundell et al. 1999).

Aus der gezeigten Verbesserung von Muskelpumpfunktion und venösem Blutfluss durch die Applikation von Kompressionsbekleidung (Agu, Baker et al. 2004;

Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976) ergibt sich die Forschungsfrage, ob Kompresssionsbekleidung bei Eisschnellläufer/innen während hoch-intensiver Belastungsintensität den Blutfluss erhöht und damit Muskeloxygenierung, aerobe Energiebereitstellung und Laufleistung verbessert. Die Ergebnisse von *Studie 1* zeigten ein leistungssteigerndes Potential bei hoch-intensiver Ausdauerbelastung > 3 min und fordern als Probanden die Involvierung von Athlet/innen mit hohem Leistungsniveau.

2.2.1 Untersuchungsdesign von Studie 2

Zehn (♀ = 6, ♂ = 4) Eisschnellläufer/innen (Alter: 23 ± 7 Jahre, Größe: 173 ±10 cm, Gewicht: 68,2 ± 13,9 kg, Körperfett: 17,8 ± 3,8 %, VO_{2peak}: 58,0 ± 5,3 $mL \cdot kg^{-1} \cdot min^{-1}$) aus dem deutschen und niederländischen Kader absolvierten zwei 3000 m Wettkampfsimulationen im Mindestabstand von einer Woche auf einer den internationalen Standards entsprechenden Eisschnelllaufbahn. In randomisierter Reihenfolge wurde die Wettkampfsimulation mit dem normalen Rennanzug absolviert und ein weiteres Mal mit dem Rennanzug und zusätzlicher Kompressionsbekleidung (94% Polyamid, 6% Lycra) an den unteren Extremitäten. Die Druckstärke der Textilien wurde mittels eines Pneumometers (SIGaT®, Ganzoni-Sigvaris, St. Gallen, Schweiz) an der Stelle des größten Umfangs von Oberschenkel und Wade bestimmt.

Während der Tests wurden kardio-respiratorische Parameter (MetaMax 3B, Cortex, Leipzig, Germany und Polar T31, Polar Electro Oy, Kempele, Finnland) und Geschwindigkeitskinetik (GPS, Cortex, Leipzig, Deutschland) mittels einer mobilen Spirometrie bestimmt. Blutvolumen und Muskeloxygenierung wurden am linken und rechten *m. quadrizeps femoris* mittels portabler NIRS-Geräte (Portamon, Artinis Medical System, Zetten, Niederlande) gemessen. Zur Bestimmung der Blutlaktatkonzentration wurde Kapillarblut aus dem Ohrläppchen vor, unmittelbar nach, 10 Minuten und 30 Minuten nach der Belastung entnommen. Das subjektive Belastungsempfinden (RPE) wurde vor und nach der Wettkampfsimulation mittels Borgs 6–20 Skala für „Gesamter Körper", „Rechter/Linker Oberschenkel" und „Rechte/Linke Wade" evaluiert (Borg 1970).

In einem separaten Labortest wurde die Körperkomposition mittels bioelektrischer Impedanzanalyse (Tanita BC 418 MA, Tanita Corp., Tokyo, Japan) gemessen. Zur Bestimmung von maximaler Sauerstoffaufnahme und Herzfrequenz wurde ein rampenförmiger Stufentest mit einer Intensitätssteigerung von 25 W à 30 Sekunden auf dem Fahrradergometer (Cyclus2, RBM Elektronik-Automation GmbH, Leipzig, Deutschland) durchgeführt (siehe Abb. 3).

Die Mittelwerte wurden mittels ANOVA und Bonferroni *post hoc* Test verglichen und das statistische Signifikanzniveau mit einem Alpha-Wert $P < 0{,}05$ festgelegt. Zur Bewertung der praktischen Relevanz wurde für alle Parameter die Effektstärke d nach Cohen (1969) berechnet.

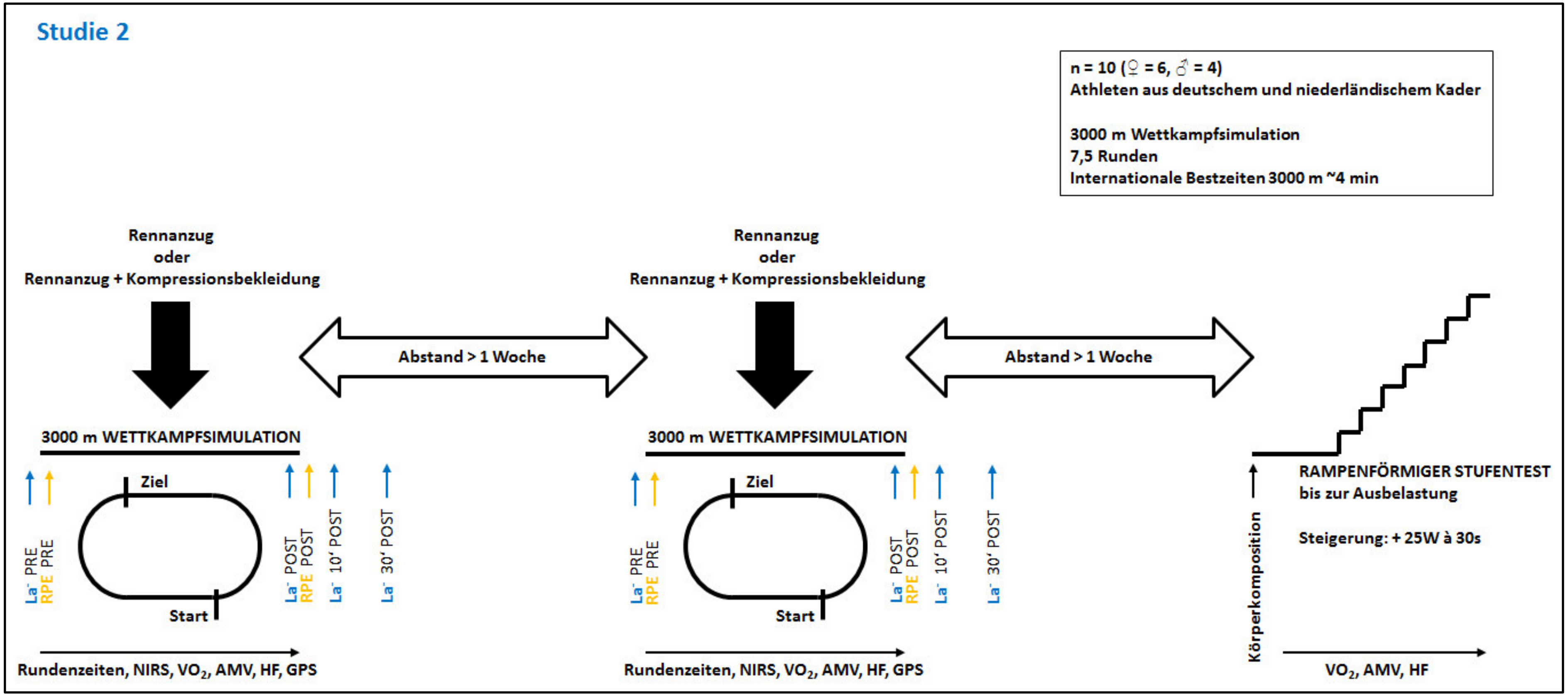

Abb. 3: Untersuchungsdesign von *Studie 2* (AMV: Atemminutenvolumen, GPS: Global Positioning System, HF: Herzfrequenz, La^-: Blutlaktat, NIRS: Nahinfrarotspektroskopie, RPE: Subjektives Belastungsempfinden (Ratings of perceived exertion), VO_2: Sauerstoffaufnahme).

2.2.2 Zusammenfassung der Ergebnisse von Studie 2

Der konventionelle Rennanzug der Eisschnellläufer/innen applizierte einen mittleren Druck von 8,3 ±2,8 mmHg am Oberschenkel und 10,7 ± 2,6 mmHg an der Wade. Wurde die Kompressionsbekleidung unter dem Rennanzug getragen, lag der Druck bei 20,3 ± 2,3 mmHg am Oberschenkel und 24,4 ± 3,1 mmHg an der Wade.

Grundsätzlich zeigte die Muskeloxygenierung während des gesamten Verlaufs der Wettkampfsimulation eine signifikant größere Reduktion im äußeren verglichen mit dem inneren *m. quadrizeps femoris* ($P < 0{,}00$; ES = 1,81). Das Blutvolumen zeigte keinen signifikanten Unterschied zwischen äußerem und innerem Bein ($P = 0{,}81$; ES = 0,52). Mit der Applikation von Kompressionsbekleidung blieben Muskeloxygenierung (niedrigstes $P = 0{,}99$; höchste ES = 0,31) und Blutvolumen (niedrigstes $P = 0{,}33$; höchste ES = 0,76) im äußeren als auch inneren *m. quadrizeps femoris* unbeeinflusst.

Das Tragen von Kompressionsbekleidung zeigte keinen Effekt auf die 3000 m Endzeit oder die Zwischenzeiten im Verlauf der Wettkampfsimulation im Vergleich zum konventionellen Rennanzug (niedrigstes $P = 0{,}24$; höchste ES = 0,43). Auch blieben alle erhobenen kardio-respiratorischen, metabolischen und subjektiven Parameter (Sauerstoffaufnahme, Atemminutenvolumen, Herzfrequenz, Blutlaktatkonzentration und subjektives Belastungsempfinden) unbeeinflusst (niedrigstes $P = 0{,}11$; höchste ES = 1,01).

2.3. ***Studie 3*:** Born DP, Holmberg HC, Goernert F, Sperlich B. (2014). **A novel compression garment with adhesive silicone stripes improves repeated sprint performance – a multi-experimental approach on the underlying mechanisms.** *BMC Sports Sci Med Rehabil*, May 30(6), 21.

Born *et al. BMC Sports Science, Medicine, and Rehabilitation* 2014, **6**:21
http://biomedcentral.com/2052-1847/6/21

BMC
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RESEARCH ARTICLE Open Access

A novel compression garment with adhesive silicone stripes improves repeated sprint performance – a multi-experimental approach on the underlying mechanisms

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In Mannschaftssportarten stellt die intermittierende Sprintfähigkeit eine leistungsentscheidende Komponente dar (Di Salvo, Baron et al. 2007; Manchado, Tortosa-Martinez et al. 2013). Dabei müssen die Athleten neben der maximalen Sprintschnelligkeit eine hohe Erholungsfähigkeit nach den einzelnen Sprints aufweisen (Bishop, Girard et al. 2011; Turner & Stewart 2013). Die Ergebnisse von *Studie 1* zeigten eine praktische Relevanz für die Verwendung von Kompressionsbekleidung bei isolierten und wiederholten Sprints als auch der Erholungsfähigkeit von Kraft- und Schnellkraftbelastungen. Es wird diskutiert, dass die Applikation von Kompressionsbekleidung die Muskelpumpfunktion erhöht und dadurch die lokale Hämodynamik verbessert (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976). Auch konnte bei intermittierender, hoch-intensiver Laufbelastung eine erhöhte Muskeloxygenierung mit Kompressionsbekleidung festgestellt werden (Sear, Hoare et al. 2010). Da jedoch das Tragen von Kompressionsbekleidung in *Studie 2* zu keinerlei Veränderung der hämodynamischen oder kardio-respiratorischen Parameter geführt hat, wurden in *Studie 3* zusätzlich biomechanische Daten zur kinematischen Bewegungsanalyse und Untersuchung der Muskelaktivität erhoben.

2.3.1 Untersuchungsdesign von Studie 3

Für *Studie 3* wurden 24 Athletinnen aus Mannschaftssport und Leichtathletik rekrutiert und jeweils 12 Athletinnen randomisiert einer von zwei Substudien zugeteilt. In beiden Substudien absolvierten die Teilnehmerinnen dasselbe Belastungsprotokoll mit und ohne Kompressionsbekleidung in randomisierter Reihenfolge. Das Belastungsprotokoll beinhaltete 30 Sprints über eine Distanz von 30 m (30 x 30 m) mit einminütiger Abgangszeit (Start eines Sprints zu jeder vollen Minute). Die Athletinnen wurden dazu angehalten, jeden einzelnen Sprint mit maximaler Intensität zu absolvieren und danach in mäßiger Laufgeschwindigkeit zur Startlinie zurück zu kehren.

Die Zeitmessung erfolgte mittels zwei Lichtschrankenpaaren (TDS Werthner Sport Consulting, Linz, Österreich). Das erste Lichtschrankenpaar war auf Höhe der Startlinie zur Auslösung der Zeitmessung platziert. Beim Durchqueren des zweiten Lichtschrankenpaares auf Höhe der Ziellinie wurde die Zeitmessung gestoppt (siehe Abb. 4). Vor dem Belastungsprotokoll wurde die Körperkomposition mittels bioelektrischer Impedanzanalyse (Tanita BC 418 MA, Tanita Corp., Tokyo, Japan) und der applizierte Druck der Kompressionshose mittels eines Pneumometers

(SIGaT®, Ganzoni-Sigvaris, St. Gallen, Schweiz) am *m. gluteus maximus, m. rectus femoris, m. vastus lateralis, m. biceps femoris* und *m. gastrocnemius medialis* bestimmt.

Zur Erhebung kardio-respiratorischer und hämodynamischer Daten wurden während des gesamten Belastungsprotokolls in Substudie 1 (n = 12, Alter: 25 ± 3 Jahre, Größe: 167 ± 3 cm, Gewicht: 61 ± 5 kg, Körperfett: 18 ± 5 %) Sauerstoffaufnahme, Atemminutenvolumen und Herzfrequenz mittels portabler Spirometrie (MetaMax 3B, Cortex, Leipzig, Deutschland und Polar T31, 1 Hz, Polar Electro Oy, Kempele, Finnland) und Muskeloxygenierung und Blutvolumen mittels kabelloser NIRS am *m. quadrizeps femoris* (Portamon, Artinis Medical System, Zetten, Niederlande) gemessen. Nach jedem Sprint wurde Kapillarblut zur Bestimmung der Laktatkonzentration aus dem Ohrläppchen entnommen und die Athletinnen nach ihrem subjektiven Belastungsempfinden (RPE) auf Borgs 6-20 Skala für „Gesamter Körper", „Oberschenkel" und „Wade" befragt (Borg 1970). Vor und nach dem Belastungsprotokoll wurde die Hauttemperatur am Oberschenkel mittels eines Temperatursensors bestimmt (MSR Modular Signal Recorder, Prospective Concepts AG, Glattbrugg, Schweiz).

In Substudie 2 (n = 12, Alter: 23 ± 2 Jahre, Größe: 169 ± 3 cm, Gewicht: 61 ± 6 kg, Körperfett: 17 ± 4 %) wurden Muskelaktivität und Lauftechnik mittels Elektromyographie und kinematischer Bewegungsanalyse untersucht. Die Muskelaktivität (EMG, TeleMyo 2400T, Noraxon Inc., Scottdale, AZ, USA) wurde während des gesamten Belastungsprotokolls am *m. gluteus maximus, m. rectus femoris, m. vastus lateralis, m. bizeps femoris,* und *m. gastrocnemius medials* erfasst. Zur Bestimmung kinematischer Daten wurde eine Kamera mit einer

Aufnahmefrequenz von 120 Hz (GoPro, San Mateo, CA, USA) rechtwinklig zur Sprintbahn mit einem Abstand von 28 m zur Startlinie platziert. Eine weitere Kamera erfasste die gesamte Sprintstrecke frontal von der Ziellinie aus.

Zum Vergleich zwischen Kompression- und der Kontrollbedingung wurden die Werte der dreißig Sprints einer jeweiligen Bedingung für Sprint 1-10, 11-20 und 21-30 gemittelt. Der Mittelwertsvergleich zur Prüfung statistisch signifikanter Unterschiede wurde mit einem Alpha-Wert von $P < 0{,}05$ mit einem gepaarten t-Test durchgeführt. Zur Bewertung der praktischen Relevanz wurde für alle Parameter die Effektstärke d nach Cohen (1969) berechnet.

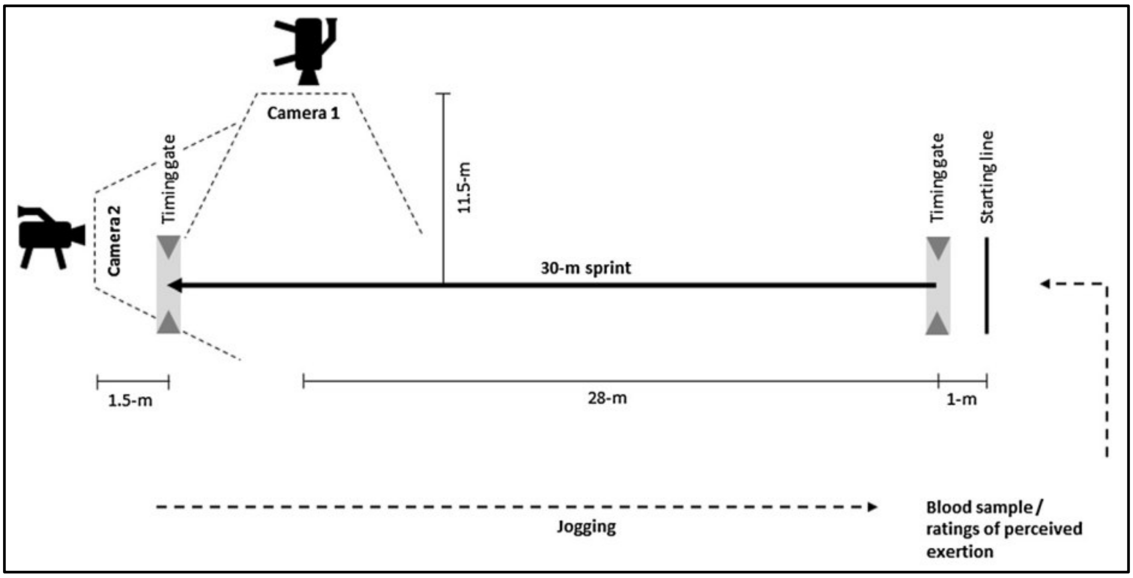

Abb. 4: Belastungsprotokoll von *Studie 3* (aus Born, Holmberg et al. 2014, *BMC Sports Sci Med Rehabil*, May 30(6), 21; reprinted with permission of BioMed Central).

2.3.2 Zusammenfassung der Ergebnisse von Studie 3

Der von der Kompressionsbekleidung applizierte Druck lag in Substudie 1 bei 19,2 ± 1,6 mmHg und in Substudie 2 bei 19,6 ± 0,8 mmHg. In beiden Substudien zeigte sich mit Kompressionsbekleidung eine signifikante Verbesserung der Sprintzeit im letzten Drittel (Sprints 21-30) des Belastungsprotokolls (niedrigstes $P < 0{,}01$; höchste ES = 0,61).

In Substudie 1 hatte die Applikation von Kompressionsbekleidung keinen Effekt auf Muskeloxygenierung und Blutvolumen (niedrigstes $P = 0{,}27$; höchste ES = 0,44). Auch alle erhobenen kardio-respiratorischen, metabolischen und thermoregulatorischen Parameter blieben unverändert (Sauerstoffaufnahme, Atemminutenvolumen, Herzfrequenz, Blutlaktatkonzentration und Hauttemperatur; niedrigstes $P = 0{,}13$; höchste ES = 0,54). Das subjektive Belastungsempfinden an der Oberschenkelmuskulatur zeigte eine signifikante Reduktion mit Kompressionsbekleidung wiederum in den letzten beiden Dritteln des Belastungsprotokolls (niedrigstes $P = 0{,}01$; höchste ES = 1,10).

In Substudie 2 zeigte sich mit Kompressionsbekleidung ein signifikant verringerter Winkel in der Hüftbeugung während der Kniehubphase (niedrigstes $P < 0{,}01$; höchste ES = 2,28). Auch vergrößerte sich die Schrittlänge (niedrigstes $P < 0{,}01$; höchste ES = 0,91) bei unveränderter Schrittfrequenz (niedrigstes $P = 0{,}34$; höchste ES = 0,20). Mit Kompressionsbekleidung zeigte sich eine erhöhte Muskelaktivität für den *m. rectus femoris* (niedrigstes $P = 0{,}01$; höchste ES = 1,24).

3. Diskussion

Studie 1 zeigte positive Effektstärken mit der Applikation von Kompressionsbekleidung bei hoch-intensiver und weniger bei submaximaler Belastungsintensität. Insbesondere hoch-intensive Ausdauer- (> 3 Minuten), Sprint- und Sprungbelastungen als auch die Erholungsfähigkeit von Kraft- und Schnellkraft scheinen durch Kompressionsbekleidung verbessert. Auch zeigten die Ergebnisse, dass bisher nur wenige Studien die Effekte von Kompressionsbekleidung bei Athlet/innen auf höchstem Leistungsniveau und insbesondere bei weiblichen Sportlern evaluiert haben. Es besteht ein Forschungsdefizit bezüglich physiologischer und biomechanischer Mechanismen, die eine mögliche Leistungssteigerung mit der Applikation von Kompressionsbekleidung bei gesunden und trainierten Athlet/innen erklären könnten.

Basierend auf den Ergebnissen von *Studie 1* wurden die Studiendesigns von *Studie 2* und *3* entwickelt. Hier zeigte sich, dass die Applikation von Kompressionsbekleidung während einer 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen keinen Effekt auf die Laufleistung hat (*Studie 2*). Mittels NIRS gemessenes Blutvolumen und Muskeloxygenierung im *m. quadrizeps femoris* sowie alle weiteren kardio-respiratorischen, metabolischen und subjektiven Parameter blieben unbeeinflusst. Dagegen führte die Applikation von Kompressionsbekleidung während intermittierender (30 x 30 m) Sprintbelastung zu signifikant verbesserter Laufleistung (*Studie 3*). Auch in dieser Untersuchung blieben alle gemessenen hämodynamischen, kardio-respiratorischen und metabolischen Parameter unbeeinflusst. Die kinematische Bewegungsanalyse zeigte jedoch eine mit Kompressionsbekleidung veränderte Lauftechnik mit vergrößerter Schrittlänge bei gleichbleibender Schrittfrequenz. Auch wurde die Sprintbelastung lokal an der Oberschenkelmuskulatur subjektiv als weniger anstrengend empfunden.

Sauerstoffaufnahme

Die Ergebnisse von *Studie 2* und *3* zeigten eine unveränderte Sauerstoffaufnahme mit Kompressionsbekleidung während der 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen und intermittierender (30 x 30 m) Sprintbelastung. Bisher konnte lediglich eine Untersuchung eine mit Kompressionsbekleidung signifikant reduzierte Sauerstoffaufnahme während submaximaler Belastungsintensität zeigen (Bringard, Perrey et al. 2006).

Bei Bewegungsformen mit sogenannten „Impact"-Belastungen (Lauf-, Sprung- und Sprintbelastungen) treten longitudinale und anterior-posteriorale Muskeloszillationen beim „Touchdown" eines jeden Schrittes auf (Doan, Kwon et al. 2003). Wie in *Studie 2* und von Sperlich, Born und Mitarbeiten (2013b) beschrieben, oszilliert ein Muskel bei der Induktion von Vibration. Bei gleichbleibender Muskelarbeit erhöht sich durch die Oszillation die Aktivität (Cardinale & Lim 2003) und der Energiebedarf der Muskulatur (Rittweger, Beller et al. 2000; Rittweger, Schiessl et al. 2001). Kompressionsbekleidung jedoch reduziert die bei „Impact"-Belastungen auftretende Muskeloszillation (Doan, Kwon et al. 2003; Mills, Scurr et al. 2011). Die sich dadurch reduzierende Muskelaktivität wird als möglicher Erklärungsansatz für die sich bei gegebener Belastungsintensität reduzierte Sauerstoffaufnahme mit Kompressionsbekleidung diskutiert (Bringard, Perrey et al. 2006).

Kritisch anzumerken ist, dass sich die Sauerstoffaufnahme in der genannten Studie bei lediglich einer (12 km·h^{-1}) von vier untersuchten Laufgeschwindigkeiten (10, 12, 14 und 16 km·h^{-1}) mit der Applikation von Kompressionsbekleidung reduzierte. Auch zeigen spätere Studien eine unveränderte Sauerstoffaufnahme bei submaximaler (Ali, Creasy et al. 2010; Dascombe, Hoare et al. 2011; Sperlich, Haegele et al. 2011) und maximaler Laufintensität (Dascombe, Hoare et al. 2011; Sperlich, Haegele et al. 2010). Bestätigt werden diese Ergebnisse von einer Studie, die isoliert die Effekte von Kompressionsbekleidung bei extern induzierter Vibration auf Muskeloszillation und Sauerstoffaufnahme untersuchte (Sperlich, Born et al. 2013b). Auch hier reduzierte niedriger und hoher Kompressionsdruck (20 und 40 mmHg) die Muskeloszillation. Die Sauerstoffaufnahme während und nach der Belastung blieb jedoch unverändert (Sperlich, Born et al. 2013b).

Zusammenfassend zeigen die Ergebnisse von *Studie 2* und *3* und die meisten bisher veröffentlichten Untersuchungen eine unveränderte Sauerstoffaufnahme mit der Applikation von Kompressionsbekleidung. Festzuhalten ist jedoch auch, dass Kompressionsbekleidung die Muskeloszillation reduziert. Im weiteren Verlauf der Arbeit bleibt zu diskutieren, inwieweit verringerte Muskeloszillation die muskuläre Ermüdung und damit die Laufleistung beeinflussen könnte.

Herzfrequenz

Die Herzfrequenz blieb in *Studie 2* und *3* mit der Applikation von Kompressionsbekleidung während der 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen und intermittierender (30 x 30 m) Sprintbelastung unverändert. Lediglich zwei Studien zeigten bisher eine signifikant reduzierte Herzfrequenz mit Kompressionsbekleidung während submaximalen Laufgeschwindigkeiten (12 und 16 $km \cdot h^{-1}$) (Dascombe, Hoare et al. 2011) und der Erholungsphase nach der Belastung (Lovell, Mason et al. 2011). Mechanistisch wird diskutiert, dass Kompressionsbekleidung die Muskelpumpfunktion und den venösen Blutfluss verbessert (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976) und dies in einer erhöhten end-diastolischen Füllung des Herzens resultieren (Ali, Caine et al. 2007). Aus dem sich daraus erhöhenden Schlagvolumen würde sich die Herzfrequenz bei gegebener Belastungsintensität verringern (Ali, Caine et al. 2007).

Kritisch anzumerken ist, dass die gezeigte Reduktion der Herzfrequenz von 3 $s \cdot min^{-1}$ (Dascombe, Hoare et al. 2011), bzw. 4-5 $s \cdot min^{-1}$ (Lovell, Mason et al. 2011), im Bereich von Thermoregulation, Dehydration, Tagesschwankung (Achten & Jeukendrup 2003) und psychologischer Faktoren induzierter Veränderung liegt (Valenti, Guida et al. 2012). Auch zeigen andere Studien eine unveränderte Herzfrequenz mit Kompressionsbekleidung während submaximaler (Ali, Creasy et al. 2010; Sperlich, Haegele et al. 2011) und maximaler Laufintensität (Ali, Creasy et al. 2011; Duffield, Cannon et al. 2010; Duffield & Portus 2007). Selbst die direkte Messung des Schlagvolumens, während submaximaler Laufbelastung, zeigte bei keiner von vier applizierten Druckstärken (10-40 mmHg) veränderte Werte durch die Kompressionsbekleidung (Sperlich, Haegele et al. 2011). Es ist zu hinterfragen, inwieweit lokal applizierte Kompressionsbekleidung an den unteren Extremitäten bei gesunden und trainierten Athlet/innen die zentrale Hämodynamik und kardiale Parameter wie Herzfrequenz oder Schlagvolumen beeinflussen kann.

Blutlaktatkonzentration

Studie 2 und *3* zeigten eine unveränderte Blutlaktatkonzentration mit der Applikation von Kompressionsbekleidung während der 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen und intermittierender (30 x 30 m) Sprintbelastung. Dieses Ergebnis wird von weiteren Studien während submaximaler (Ali, Creasy et al. 2010; Sperlich, Haegele et al. 2011) als auch hoch-intensiver Belastung bestätigt (Duffield, Cannon et al. 2010; Duffield & Portus 2007; Sperlich, Born et al. 2013b; Sperlich, Haegele et al. 2010).

Andere Studien jedoch zeigten eine verringerte Blutlaktatkonzentration nach hoch-intensiver Belastung mit Kompressionsbekleidung (Berry & McMurray 1987; Chatard, Atlaoui et al. 2004; Rider, Coughlin et al. 2014; Sperlich, Born et al. 2013c). Auch Kemmler, von Stengel und Mitarbeiter (2009) stellten eine Rechtsverschiebung der Laktatleistungskurve mit Kompressionsbekleidung während stufenförmigem Belastungsprotokoll fest. Interpretiert wurden diese Ergebnisse als eine verbesserte Laufökonomie bei submaximaler Belastungsintensität. Die Bestimmung der Laktatkonzentration im Kapillarblut gibt jedoch keinen direkten Aufschluss über Art und Ort des laktatproduzierenden bzw. –eliminierenden Gewebes (Sperlich, Born et al. 2013c). Eine verringerte Blutlaktatkonzentration mit Kompressionsbekleidung steht somit nicht in direktem Zusammenhang mit verbesserter Laufleistung oder –ökonomie. Besonders da mehrere Erklärungsansätze diskutiert werden, wie Kompressionsbekleidung zur verringerten Blutlaktatkonzentration geführt haben könnte.

Davon ausgehend, dass Kompressionsbekleidung die Hämodynamik verbessert und den Blutfluss erhöht (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lawrence &

Kakkar 1980; Lewis, Antoine et al. 1976), wäre ein erhöhter Abtransport des entstehenden Laktats aus der Arbeitsmuskulatur zu anderen Geweben mit hoher oxidativer Kapazität möglich (Berry & McMurray 1987; Chatard, Atlaoui et al. 2004). Auch andere Studien diskutieren eine erhöhte Umverteilung des entstehenden Laktats in andere, laktatverstoffwechselnde Gewebe als möglichen Mechanismus für verringerte Blutlaktatkonzentration bei hoch-intensiver Belastung (Sperlich, Born et al. 2013c). Als alternativer Erklärungsansatz könnte aus einem erhöhten Blutfluss mit Kompressionsbekleidung eine verbesserte Sauerstoffverfügbarkeit in der Muskulatur und folglich eine höhere aerobe Energiebereitstellung und verringerte Entstehung von anaeroben Stoffwechselzwischenprodukten (Laktatmolekülen) resultieren (Berry & McMurray 1987). Die Autoren stellen diesen Mechanismus jedoch durch die ausbleibende Veränderung der Sauerstoffaufnahme in Frage (Berry & McMurray 1987). Auch in späteren Studien bleibt die Sauerstoffaufnahme, bei reduzierter Blutlaktatkonzentration, unverändert (Kemmler, von Stengel et al. 2009; Rider, Coughlin et al. 2014; Sperlich, Born et al. 2013c).

Konträr diskutiert wird, dass die Applikation von Kompressionsbekleidung den Blutfluss bei gesunden und trainierten Athlet/innen sogar reduzieren könnte. Dies würde den Austritt des entstehenden Laktats aus dem Muskel in die Blutbahn verringern und die im Kapillarblut reduzierte Laktatkonzentration erklären (Berry & McMurray 1987; Chatard, Atlaoui et al. 2004). Allerdings würde dies bedeuten, dass bei der Belastung entstehende Laktatmoleküle in der Arbeitsmuskulatur verbleiben würden und somit die intramuskuläre Laktatkonzentration mit Kompressionsbekleidung erhöht wäre.

Das mittels NIRS gemessene Blutvolumen in *Studie 2* und *3* blieb zwar unverändert. Jedoch liefert dieses Verfahren nur einen indirekten Hinweis auf den tatsächlichen Blutfluss. *In vivo* Untersuchungen mitttels PET zeigen einen reduzierten Blutfluss mit Kompressionsbekleidung bei gesunden und trainierten Athleten in Ruhe und nach hoch-intensiver Belastung (Sperlich, Born et al. 2013a). Damit ist anzunehmen, dass die von Kemmler, von Stengel und Mitarbeiter (2009) gezeigte Rechtsverschiebung der Laktatleistungskurve mit Kompressionsbekleidung auf einen durch reduzierten Blutfluss verringerten Austritt des Laktats in die Blutbahn zurückgeht. Zwar war die Laufleistung in der vorliegenden Studie mit Kompressionsbekleidung und reduzierter Blutlaktatkonzentration verbessert (Kemmler, von Stengel et al. 2009), jedoch zeigt eine andere Studie den umgekehrten Effekt und eine geringere Laufleistung mit Kompressionsbekleidung und reduzierter Blutlaktatkonzentration (Rider, Coughlin et al. 2014).

Zusammenfassend ist kritisch zu hinterfragen, inwieweit eine verringerte Blutlaktatkonzentration mit Kompressionsbekleidung als positiver Effekt interpretiert werden kann. Aus den bisher publizierten Studien lässt sich kein einheitlicher Zusammenhang zwischen mit Kompressionsbekleidung reduzierter Blutlaktatkonzentration und verbesserter Leistung bei hoch-intensiver Belastung zeigen (Berry & McMurray 1987; Chatard, Atlaoui et al. 2004; Kemmler, von Stengel et al. 2009; Rider, Coughlin et al. 2014; Sperlich, Born et al. 2013c). Folglich müssen andere Mechanismen als veränderte Blutlaktatkonzentration zu der in *Studie 3* gezeigten Leistungssteigerung mit Kompressionsbekleidung während intermittierender (30 x 30 m) Sprintbelastung geführt haben.

Subjektives Belastungsempfinden

Während *Studie 1* eine praktische Relevanz für ein verbessertes subjektives Belastungsempfinden mit Kompressionsbekleidung zeigte, bestätigte *Studie 3* dieses Ergebnis während intermittierender (30 x 30 m) Sprintbelastung. Hier wurde die Belastung an der Oberschenkelmuskulatur subjektiv als weniger anstrengend empfunden. Grundsätzlich ist die Oberschenkelmuskulatur bei Sprintbelastungen eine hoch belastete und hauptantriebsrelevante Muskelgruppe (Delecluse 1997) und ein verbessertes Belastungsempfinden könnte einen Teil der gezeigten Leistungssteigerung erklären.

Ein interessantes Ergebnis zeigt der Vergleich weiterer Studien, die das subjektive Belastungsempfinden untersucht haben. Bei hoch-intensiver Lauf-, Sprint- und wiederholter Sprungbelastung (Duffield, Edge et al. 2008; Faulkner, Gleadon et al. 2013; Kraemer, Bush et al. 2001a; Kraemer, Bush et al. 2001b; Kraemer, Flanagan et al. 2010), und weniger bei submaximaler und moderater Belastungsintensität (Ali, Creasy et al. 2010, 2011; Sperlich, Haegele et al. 2010), zeigte sich ein verbessertes subjektives Belastungsempfinden. Damit scheinen Athlet/innen besonders bei intensiver, hohen Muskelschmerz induzierender Belastung von Kompressionsbekleidung zu profitieren.

Grundsätzlich kann nicht ausgeschlossen werden, dass reduzierter Muskelschmerz auf einem sogenannten „Placebo"-Effekt basiert. Dennoch erscheint eine geblindete Testung von Kompressionsbekleidung nicht in Gänze möglich, da die Proband/innen den applizierten oder nicht vorhandenen Druck wahrnehmen würden. Allerdings nehmen auch psychologische Faktoren wie das subjektive Belastungsempfinden entscheidenden Einfluss auf die körperliche Leistungsfähigkeit (Duffield & Portus

2007; Kraemer, Bush et al. 1998). In *Studie 3* reduzierte die Kompressionsbekleidung den Muskelschmerz und verbesserte das subjektive Belastungsempfinden besonders in der zweiten Hälfte der intermittierenden (30 x 30 m) Sprintbelastung. Gleichzeitig zeigte sich in diesem Teil des Belastungsprotokolls eine im Vergleich zur Kontrollbedingung verbesserte Sprintleistung. Unabhängig physiologischer und biomechanischer Effekte scheint ein verbessertes Belastungsempfinden zur Leistungssteigerung während intermittierender (30 x 30 m) Sprintbelastung beigetragen zu haben.

Blutfluss und Muskeloxygenierung

In klinischen Studien bei Patienten mit venöser Insuffizienz konnte gezeigt werden, dass die Applikation von Kompressionsbekleidung die Muskelpumpfunktion, den venösen Blutfluss (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976) und die Muskeloxygenierung erhöht (Agu, Baker et al. 2004). Dieser Mechanismus wurde zum Anlass genommen, auch bei gesunden und trainierten Athlet/innen nach einer Leistungssteigerung mit Kompressionsbekleidung während sportlicher Belastung durch Erhöhung von Blutfluss und Sauerstoffverfügbarkeit zu suchen. Während in *Studie 2* und *3* mittels NIRS gemessenes Blutvolumen und Muskeloxygenierung unverändert blieben, zeigt die aktuelle wissenschaftliche Datenlage ein heterogenes Bild.

Bei hoch-intensiver Laufbelastung konnte gezeigt werden, dass die Applikation von Kompressionsbekleidung zu einem gesteigerten, mittels NIRS gemessenen, Blutvolumen im *m. quadrizeps femoris* führt (Dascombe, Hoare et al. 2011). Dieser

Effekt wurde auf einen durch die Kompressionsbekleidung verbesserten venösen Blutfluss zurückgeführt. Widersprüchlich erscheint, dass die Kompressionsbekleidung in der genannten Studie zu einer signifikant reduzierten Muskeloxygenierung führte (Dascombe, Hoare et al. 2011). Im Gegensatz dazu zeigten andere Studien bei ebenfalls hoch-intensiver Belastung eine erhöhte Muskeloxygenierung mit Kompressionsbekleidung bei jedoch unverändertem Blutvolumen (Scanlan, Dascombe et al. 2008; Sear, Hoare et al. 2010). Eine wiederum andere Studie stellte fest, dass Kompressionsbekleidung die Muskeloxygenierung bei niedriger, aber nicht höherer Belastungsintensität verbesserte. Daten zum Blutvolumen werden jedoch nicht beschrieben (Boucourt, Bouhaddi et al. 2014).

Aus der Literatur lassen sich jedoch auch Erklärungsansätze für die teils widersprüchlichen Ergebnisse entnehmen. Methodenkritisch beschreibt eine Studie, dass sich die mittels NIRS gemessene Muskeloxygenierung verbessert, wenn lediglich der Anpressdruck des Messkopfes erhöht wird (Menetrier, Mourot et al. 2011). Da der NIRS-Messkopf aus messtechnischen Gründen direkt auf der Haut und unter der Kompressionsbekleidung angebracht werden muss, wird dieser mit steigendem Kompressionsdruck tiefer in die Haut gedrückt und erfasst möglichweise tiefer liegende Muskelschichten als bei der Kontrollbedingung. Auch sich an der Messstelle durch den Anpressdruck verdichtendes Haut- und Muskelgewebe könnte die NIRS-Messung beeinflussen. Dies Phänomen liefert einen kritischen Erklärungsansatz für die gezeigte Korrelation zwischen sich erhöhender Druckstärke der Kompressionsbekleidung und steigender Muskeloxygenierung (Coza, Dunn et al. 2012). Es bleibt zu diskutieren, ob eine mit Kompressionsbekleidung erhöhte Muskeloxygenierung bei gesunden und trainierten Athlet/innen auf messmethodische Gründe oder einen tatsächlich gesteigerten Blutfluss zurückgehen.

Eine neuere Interventionsstudie zeigte bei einem 10-wöchigen Krafttraining mit Kompressionsbekleidung und hoher Druckstärke eine substantiell höhere Kraftanpassung als bei der Kontrollbedingung ohne Kompressionsbekleidung. Interessanterweise wird als zugrunde liegender Mechanismus die okkludierende, also Blutfluss reduzierende, Wirkung der Kompressionsbekleidung genannt. Messergebnisse zu Blutfluss und Muskeloxygenierung liefert die Studie nicht (Godawa, Credeur et al. 2012). Die Untersuchung von Sperlich, Born und Mitarbeitern (2013a) unterstützt jedoch die Annahme einer, bei gesunden und trainierten Athlet/innen, möglicherweise beeinträchtigten Hämodynamik mit Kompressionsbekleidung. Mittels des nuklear-medizinischen Verfahrens PET wurde mit der Applikation eines hohen Kompressionsdrucks (~37 mmHg) ein reduzierter *in vivo* Blutfluss in Ruhe und nach hoch-intensiver Belastung gemessen (Sperlich, Born et al. 2013a).

Zusammen mit der widersprüchlichen internationalen Datenlage und den Ergebnissen von *Studie 2* und *3* ist kritisch zu hinterfragen, inwieweit Kompressionsbekleidung zu einer verbesserten Hämodynamik bei gesunden und trainierten Athlet/innen führt. Der blutflusssteigernde Effekt, der bei venös erkrankten Patienten mit der Applikation von Kompressionsbekleidung gezeigt wurden, scheint nicht ohne weiteres auf ein gesundes und funktionsfähiges Venensystem übertragbar. Auch muss nach anderen Erklärungsansätzen für die in *Studie 3* gezeigte Leistungssteigerung während intermittierender (30 x 30 m) Sprintbelastung, als die rein physiologischen Mechanismen, gesucht werden.

Länge der Sprintbelastung

Studie 1 zeigte eine praktische Relevanz für eine gesteigerte Leistung mit Kompressionsbekleidung bei Sprintbelastungen und der Erholungsfähigkeit von Kraft- und Schnellkraft. Bestätigt werden diese Ergebnisse in *Studie 3* bei intermittierender (30 x 30 m) Sprintbelastung. Während bisherige Studien zwar hohe Effektstärken bezüglich einer gesteigerten Laufleistung bei intermittierender, hoch-intensiver Belastung zeigten (Goh, Laursen et al. 2010; Higgins, Naughton et al. 2009; Sear, Hoare et al. 2010), blieb eine signifikante Leistungsverbesserung bei intermittierender Sprintbelastung aus (Duffield, Cannon et al. 2010; Duffield & Portus 2007; Higgins, Naughton et al. 2009; Houghton, Dawson et al. 2009).

Einen möglichen Erklärungsansatz für die ausbleibenden signifikanten Ergebnisse liefern die verwendeten Belastungsprotokolle. Stets wurden kürzere Sprintdistanzen (15-20 m) (Duffield, Cannon et al. 2010; Duffield & Portus 2007; Higgins, Naughton et al. 2009; Houghton, Dawson et al. 2009) als die in *Studie 3* (30 m) verwendet. Allerdings sind die ersten 10 m eines jeden Sprints durch eine weit nach vorne gebeugte Körperhaltung charakterisiert und hängen primär von der Kraft- und Schnellkraft der Beinstreckmuskulatur ab (Debaere, Jonkers et al. 2013; Mero, Komi et al. 1992). Erst in der späteren Sprintphase mit aufrechter Körperhaltung gewinnen technische Aspekte wie schneller Fußaufsatz, explosive dorsale Beinbeschleunigung während der Standphase und eine schnelle ventrale Beinbeschleunigung während der Schwung-/Rückholphase an Bedeutung (Ciacci, Di Michele et al. 2010; Hunter, Marshall et al. 2005; Mero, Komi et al. 1992). In dieser Sprintphase scheint die Kompressionsbekleidung, wie im Folgenden diskutiert, durch veränderte Propriozeption, Feinmotorik und Lauftechnik die Leistung zu verbessern.

Lauftechnik: Schrittlänge und -frequenz

In *Studie 3* zeigte sich während intermittierender (30 x30 m) Sprintbelastung mit Kompressionsbekleidung eine vergrößerte Schrittlänge bei gleichbleibender Schrittfrequenz. Da sich die Laufgeschwindigkeit aus dem Produkt von Schrittlänge und -frequenz ergibt (Hunter, Marshall et al. 2004), resultierte die mit Kompressionsbekleidung vergrößerte Schrittlänge, bei gleichbleibender Schrittfrequenz, in einer verbesserten Sprintleistung.

Grundsätzlich verhalten sich Schrittlänge und –frequenz in einer negativen Interaktion zueinander, und eine Vergrößerung des Einen geht mit einer Verringerung des Anderen einher (Debaere, Jonkers et al. 2013; Hunter, Marshall et al. 2004). Bei Elite-Sprintern konnte jedoch festgestellt werden, dass eine größere Schrittlänge eine der Leistungskomponenten darstellt, die den Unterschied zwischen Sieger und Athleten auf den nachfolgenden Platzierungen ausmacht (Krzysztof & Mero 2013).

Auch bei sprint-trainierten aber nicht-elitären Athleten, ähnlich des Leistungsniveaus der Probandinnen aus *Studie 3*, wird der Schrittlänge eine wichtige Bedeutung zugeschrieben. Hier korrelierte die Schrittlänge mit der Geschwindigkeit während der Beschleunigungsphase in den ersten 10 m des Sprints (Lockie, Murphy et al. 2013). Auch ging mit der größeren Schrittlänge eine höhere vertikale und horizontale Kraftentfaltung einher (Lockie, Murphy et al. 2013). Damit scheint die Applikation von Kompressionsbekleidung die Lauftechnik zu verändern und die Leistungssteigerung bei intermittierender (30 x 30 m) Sprintbelastung mit vergrößerter Schrittlänge und gleichbleibender Schrittfrequenz zu erklären.

Propriozeption und Feinmotorik

Es wurde gezeigt, dass die Applikation von Kompressionsbekleidung Propriozpetion, Feinmotorik und Balance verbessert (Michael, Dogramaci et al. 2014; Pearce, Kidgell et al. 2009). So erhöhte sich mit Kompressionsbekleidung die Trefferquote während eines feinkoordinativen Bewegungsablaufes nach hoch-intensiver Belastung und im Zustand von belastungsinduziertem Muskelschmerz (Pearce, Kidgell et al. 2009). Auch die Balance war mit Kompressionsbekleidung verbessert, wenn das visuelle Feedback eingeschränkt wurde (Michael, Dogramaci et al. 2014).

Mechanorezeptoren in Haut, Muskeln, Sehnen, Bändern und Kapseln geben konstante Rückmeldung über die Gelenkwinkel, Position, Geschwindigkeit und Beschleunigung von Rumpf und Extremitäten (Birmingham, Kramer et al. 1998). Man geht davon aus, dass der Druck, der von der Kompressionsbekleidung auf die Haut aufgebracht wird, die oberflächlichen Mechanorezeptoren aktiviert. Die dadurch erhöhte neuronale Rückmeldung aus den Extremitäten verbessert Propriozpetion, Feinmotorik und Balance (Barrack, Skinner et al. 1989; Kuster, Grob et al. 1999; Perlau, Frank et al. 1996).

Es ist davon auszugehen, dass durch eine verbesserte neuronale Rückmeldung mit Kompressionsbekleidung besonders komplexere Bewegungsabläufe (z.B. Sprint- und Sprungbelastungen) optimiert werden. So zeigte die Applikation von Kompressionsbekleidung während isolierter, isometrischer Plantarflexion keinen Effekt auf muskuläre Ermüdung und Erholungsfähigkeit (Maton, Thiney et al. 2006). Für Sprintbelastungen jedoch, stellen Propriozpetion, Feinmotorik und Balance wichtige Zubringerleistungen dar um eine optimale Lauftechnik zu gewährleisten und diese bei eintretender Ermüdung aufrechtzuerhalten (Hrysomallis 2011).

Während die Leistung während Start- und initialer Beschleunigungsphase primär durch die maximale Kraftentfaltung der Beinstreckmuskulatur determiniert ist, nehmen in der späteren Phase eines jeden Sprints (> 10 m) technische und koordinative Aspekte entscheidenden Einfluss auf die Sprintleistung (Debaere, Jonkers et al. 2013; Mero, Komi et al. 1992). Hier befindet sich der/die Athlet/in in einer aufrechten Körperhaltung und eine schnelle Rückholphase des Beines mit möglichst geringem Trägheitsmoment, Fußaufsatz nahe am Körperschwerpunkt zur Reduktion von Bremskräften und ein optimales Verhältnis von Schrittlänge und Schrittfrequenz sind wichtige Teilaspekte der Lauftechnik (Ciacci, Di Michele et al. 2010; Debaere, Jonkers et al. 2013; Hunter, Marshall et al. 2005; Mero, Komi et al. 1992). In dieser Sprintphase scheint die mit Kompressionsbekleidung erhöhte Propriozeption, Feinmotorik und Balance die Leistung zu verbessern. Besonders bei eintretender muskulärer Ermüdung, im Verlauf der intermittierenden (30 x 30 m) Sprintbelastung, scheint so eine optimale Lauftechnik aufrechterhalten und damit die intermittierende Sprintleistung mit der Applikation von Kompressionsbekleidung verbessert zu werden.

Muskeloszillation

Grundsätzlich reduziert die Applikation von Kompressionsbekleidung die longitudinale und anterior-posteriorale Muskeloszillation, die bei sogenannten „Impact"-Belastungen (Sprint-, Sprung-, Laufbelastungen) auftritt (Doan, Kwon et al. 2003; Mills, Scurr et al. 2011). Wie bereits im Unterkapitel „*Sauerstoffaufnahme*" diskutiert, scheint sich reduzierte Muskeloszillation nicht auf Laufökonomie und Sauerstoffaufnahme bei submaximaler Laufbelastung auszuwirken (Ali, Creasy et al.

2010; Bringard, Perrey et al. 2006; Dascombe, Hoare et al. 2011; Sperlich, Haegele et al. 2011). Während maximaler, wiederholter Sprungbelastung jedoch, wird eine mit Kompressionsbekleidung reduzierte Muskeloszillation als Grund für verringerte muskuläre Ermüdung und gesteigerte Leistung diskutiert (Kraemer, Bush et al. 1996; Kraemer, Bush et al. 1998).

Es lässt sich der Mechanismus zugrunde legen, dass ein Muskel bei der Induktion von Vibration oszilliert und dies die Muskelaktivität erhöht (Cardinale & Lim 2003) und die muskuläre Ermüdung beschleunigt (Shinohara 2005). Appliziert man Kompressionsbekleidung und reduziert somit die bei „Impact"-Belastungen auftretende Muskeloszillation, könnte dies zu verringerter muskulärer Ermüdung führen und somit die Leistung bei wiederholter Sprint- und Sprungbelastung steigern (Duffield, Cannon et al. 2010; Kraemer, Bush et al. 1996; Kraemer, Bush et al. 1998).

Während sich Muskelermüdung nur schwer quantifizieren lässt, liefert eine jüngst veröffentlichte Studie einen Hinweis auf die Effekte von mit Kompressionsbekleidung reduzierter Muskeloszillation. Hier reduzierte die Applikation von Kompressionsbekleidung während 40-minütiger Laufbelastung mit negativer Steigung (- 10%) die belastungsinduzierten Mikroverletzungen im Vergleich zur Kontrollbedingung um ~27% (Valle, Til et al. 2013). Die Autoren führen die Reduktion der belastungsinduzierten Mikroverletzungen auf die durch Kompressionsbekleidung verringerte Muskeloszillation zurück. Es bleibt zu diskutieren, ob reduzierte Muskeloszillation bereits während der Belastung die muskuläre Ermüdung verringert und so zur Leistungssteigerung mit Kompressionsbekleidung während intermittierender (30 x 30 m) Sprintbelastung in *Studie 3* beigetragen hat.

Hoch-intensive Ausdauerbelastung

Die aus den Ergebnissen von *Studie 1* erwartete Leistungssteigerung bei hoch-intensiver Ausdauerbelastung wurde in *Studie 2* während der 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen nicht bestätigt. Gründe für die Diskrepanz liefern die in bisherigen Untersuchungen verwendeten Leistungstests. Eine Vielzahl der Studien, die in die Effektstärkenberechung von *Studie 1* eingeflossen sind, haben die Leistung mittels sogenannter „Open-end"-Tests (auch „Time-to-exhaustion"-Tests) gemessen. Diese werden mit einer geringeren Reliabilität (Variationskoeffizient > 10%) als ein in *Studie 2* verwendeter „Closed-end"-Test (Variationskoeffizient < 5%) beschrieben (Currell & Jeukendrup 2008).

Neuere Studien, die nach der Datenerhebung von *Studie 1* veröffentlicht wurden, bestätigen den Befund von *Studie 2*. In „Closed-end"-Tests zeigte die Applikation von Kompressionsbekleidung keinen Effekt während eines 15 minütigen Zeitfahrens auf dem Rad (Driller & Halson 2013) oder einer 5 km Wettkampfsimulation bei Läufern (Barwood, Corbett et al. 2013). Auch bei längerer Belastungszeit während eines 15,6 km Crosslaufs (Vercruyssen, Easthope et al. 2014) oder einer Triathlon Halbdistanz, zeigte sich keine Leistungssteigerung mit Kompressionsbekleidung (Del Coso, Areces et al. 2014). Weitere Studien untersuchten die Ausdauerleistung bei hoch-intensiver Oberkörperarbeit. Hier zeigte sich weder bei einer Wettkampfsimulation am Skilanglauf- (3 x 3 min Team-Sprint) (Sperlich, Born et al. 2013c), noch am Kayakergometer (4 min Zeitfahren) ein leistungssteigernder Effekt mit Kompressionsbekleidung (Dascombe, Laursen et al. 2013).

Mechanistisch liefert die in klinischen Studien bei Patienten mit venöser Insuffizienz mit Kompressionsbekleidung gezeigte Blutflusssteigerung (Agu, Baker et al. 2004;

Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976) die Grundlage für eine mögliche Verbesserung der Ausdauerleistung bei gesunden und trainierten Athlet/innen. Wie bereits im Abschnitt „*Blutfluss und Muskeloxygenierung*“ diskutiert, zeigt jedoch die aktuelle Datenlage, dass Kompressionsbekleidung beim gesunden und trainierten Venensystem, zu keinem veränderten Blutfluss zu führen scheint. Daher ist auch eine Leistungssteigerung während hoch-intensiver Ausdauerbelastung (> 3 min) zu hinterfragen. Vielmehr scheinen sich ergogene Effekte von Kompressionsbekleidung, bei gesunden und trainierten Athlet/innen, während wiederholter Schnellkraft- und Sprintbelastung zu manifestieren und auf anderen als den rein physiologischen Mechanismen zu basieren.

Zukünftige Studien

Wie in *Studie 1* beschrieben, zeigen bisherige Untersuchungen eine hohe Streuung bezüglich der applizierten Druckstärke der Kompressionsbekleidung (8-40 mmHg). In *Studie 3* konnte zwar ein leistungssteigernder Effekt mit einem Druck von ~20 mmHg gezeigt werden. Da jedoch nur eine Druckstärke untersucht wurde, bleibt die Frage nach der optimalen Druckstärke mit dem höchsten leistungssteigernden Effekt offen. Von Interesse wäre eine detaillierte Untersuchung zum Zusammenhang zwischen Höhe der applizierten Druckstärke, physiologischer und biomechanischer Effekte und einer potentiellen Leistungssteigerung mit Kompressionsbekleidung während intermittierender Sprintbelastung.

In einer Vielzahl von Studien wurde Kompressionsbekleidung mit einer progressiv abfallenden Druckverteilung von distal nach proximal appliziert (*Studie 1*). Dies hat zum Ziel, wie in klinischen Studien bei Patienten mit venöser Insuffizienz gezeigt, die Muskelpumpfunktion und den venösen Blutfluss aus den unteren Extremitäten in Richtung des Herzens zu unterstützen (Agu, Baker et al. 2004; Ibegbuna, Delis et al. 2003; Lawrence & Kakkar 1980; Lewis, Antoine et al. 1976). Nach den Ergebnissen von *Studie 2* und *3*, scheint die Leistungssteigerung mit Kompressionsbekleidung bei gesunden und trainierten Athlet/innen jedoch anderen Mechanismen als einem erhöhten Blutfluss zugrunde zu liegen.

Auch zeigte eine neue Studie in diesem Zusammenhang, dass kein Unterschied im Ausmaß der muskulären Ermüdung nach submaximaler Belastung zwischen Kompressionsbekleidung mit einem progressiv abfallenden oder homogen verteilten Druckprofil besteht. Quantifiziert wurde die muskuläre Ermüdung hier annäherungsweise mittels bildgebender Verfahren anhand des intramuskulären pH-Wertes und des Verhältnisses zwischen freien intramuskulären Phosphaten und der Creatin-Phosphat Konzentration (Miyamoto & Kawakami 2015). In zukünftigen Studien ist daher die optimale Druckverteilung der Kompressionsbekleidung für Training und Wettkampf zu überdenken. Es bleibt zu evaluieren, ob die in klinischen Studien gezeigte progressive Druckverteilung die vorteilhafteste für die Anwendung bei gesunden und trainierten Athlet/innen ist. Auch wurde gezeigt, dass der Kompressionsdruck durch Körperposition und –haltung verändert wird (Brophy-Williams, Driller et al. 2014). Von Interesse wäre daher eine detaillierte Untersuchung verschiedener Druckstärken und -verteilungen während verschiedener Sportarten und Bewegungsmuster.

Eine jüngst veröffentlichte Studie konnte feststellen, dass der von der Kompressionsbekleidung applizierte Druck nach der Belastung, im Vergleich zum

Beginn der Untersuchung, signifikant abgesunken war (Faulkner, Gleadon et al. 2013). Dieser Befund hat eine besondere Bedeutung für die praktische Anwendung von Kompressionsbekleidung in Training und Wettkampf. Interessant wäre zu untersuchen, in welchem Ausmaß die Kompressionsbekleidung den applizierten Druck nach mehrfachem Tragen und Waschen verliert. Auch stellt sich die Frage, welche Textilformen (z.B. Faserbeschaffenheit und Webart) die Druckeigenschaften am besten erhalten.

In *Studie 2* zeigte die Applikation von Kompressionsbekleidung keinen Effekt auf die Leistung während der 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen. Vor dem Hintergrund der Ergebnisse von *Studie 3* wäre eine weitere Untersuchung der kürzeren Sprintwettkampfstrecken (beispielsweise 500 m) und der Startleistung im Eisschnelllauf von Interesse. Nach dem in *Studie 3* keiner der physiologischen Parameter, jedoch die biomechanische Datenerhebung, Erklärungsansätze für die gesteigerte Leistung geliefert haben, könnten in weiteren Untersuchungen im Eisschnelllauf kinematische Parameter und Technikanalysen Aufschluss über mögliche Effekte von Kompressionsbekleidung geben.

Kritisch anzumerken ist, dass das langjährige Training von Athlet/innen auf höchstem Leistungsniveau zur Einschleifung optimaler motorischer Abläufe führt und die Bewegungsausführung resistent gegen äußere Einflüsse macht. Damit scheint es als schwierig auf diesem Leistungsniveau durch die Applikation von Kompressionsbekleidung eine Technikveränderung mit messbarer Leistungssteigerung hervorzurufen. Es wirft die Frage auf, ob ergogene Effekte von Kompressionsbekleidung in Abhängigkeit von Trainingshintergrund und Leistungsniveau auftreten.

Die in *Studie 3* gezeigte Leistungssteigerung mit Kompressionsbekleidung und die hohe Relevanz intermittierender Sprintbelastung im Spielsport (Di Salvo, Baron et al. 2007; Manchado, Tortosa-Martinez et al. 2013), fordert nach weiteren Untersuchungen der gezeigten Effekte unter Feldbedingung. In zukünftigen Studien könnten Laufweg- und Aktionsanalysen bei Wettkampfsimulationen im Spielsport Aufschluss zu den Effekten von Kompressionsbekleidung auf die intermittierende Sprintleistung unter Feldbedingungen geben. Es ist jedoch anzumerken, dass Spielanalysen unter Realbedingungen nur einen Hinweis auf mögliche, durch Kompressionsbekleidung induzierte, Effekte geben können. Spielsituationen im Mannschaftssport werden durch eine Vielzahl von Faktoren, wie Gegner, Mannschaftsaufstellung oder Witterungsbedingung, zum Teil stark beeinflusst, und können nur schwer standardisiert werden (Born, Hoppe et al. 2014).

4. Zusammenfassung und Fazit

Es wurde gezeigt, dass die Applikation von Kompressionsbekleidung zu einem erhöhten Blutfluss bei Patienten mit venöser Insuffizienz führt (Agu, Baker et al. 2004) und das Thromboserisiko bei bettlägerigen und postoperativen Patienten reduziert (Agu, Hamilton et al. 1999). Davon ausgehend, dass Kompressionsbekleidung auch bei gesunden und trainierten Athlet/innen den Blutfluss steigert, wurde in einer Vielzahl von Studien nach einer gesteigerten Leistung während langanhaltender Ausdauerbelastung gesucht. Die Ergebnisse sind jedoch oft widersprüchlich und zeigen eine heterogene Datenlage bezüglich ergogener Effekte von Kompressionsbekleidung bei gesunden und trainierten Athlet/innen.

Studie 1 zeigte positive Effektstärken mit der Applikation von Kompressionsbekleidung bei hoch-intensiver und weniger bei submaximaler Belastungsintensität. Es manifestierte sich ein leistungssteigerndes Potential während hoch-intensiver Ausdauer- (> 3 Minuten), Sprint- und Sprungbelastungen als auch für die Erholungsfähigkeit von Kraft- und Schnellkraft. Während Unklarheit über eine mögliche blutflusssteigernde Wirkung von Kompressionsbekleidung bei gesunden und trainierten Athlet/innen herrscht, werden eine Vielzahl weiterer phyiologischer und biomechanischer Mechanismen diskutiert, die zu einer potentiellen Leistungssteigerung führen könnten.

Basierend auf *Studie 1* wurden die Studiendesigns von *Studie 2* und *3* entwickelt. Es zeigte sich, dass die Applikation von Kompressionsbekleidung keinen Effekt auf die Leistung bei einer 3000 m Wettkampfsimulation bei hoch-trainierten Eisschnellläufer/innen hat. Mittels NIRS gemessenes Blutvolumen und

Muskeloxygenierung im *m. quadrizeps femoris* als auch alle gemessenen kardio-respiratorischen, metabolischen und subjektiven Parameter blieben unverändert. Dagegen führte die Applikation von Kompressionsbekleidung bei wiederholter (30 x 30 m) Sprintbelastung zu signifikant verbesserter Laufleistung (*Studie 3*). Interessanterweise blieben auch in dieser Untersuchung alle gemessenen hämodynamischen, kardio-respiratorischen und metabolischen Parameter unbeeinflusst. Die kinematische Datenerhebung zeigte jedoch, dass Kompressionsbekleidung zu veränderter Lauftechnik führt und die Schrittlänge bei gleichbleibender Schrittfrequenz vergrößert. Auch wurde die Sprintbelastung lokal an der Oberschenkelmuskulatur subjektiv als weniger anstrengend empfunden.

Zusammenfassend lässt sich keine globale Aussage zu einer Leistungssteigerung durch Kompressionsbekleidung in Training und Wettkampf tätigen. Abhängig von Belastungsart und –intensität manifestierten sich ergogene Effekte bei hoch-intensiver Lauf- insbesondere intermittierender Sprintbelastung. Im Zusammenhang mit einer weiteren Untersuchung (Sperlich, Born et al. 2013a) scheint die Leistungssteigerung jedoch nicht auf einer veränderten Hämodynamik zu basieren. Bei gesunden und trainierten Athlet/innen konnte weder mittels des nuklarmedizinischen Verfahrens PET (Sperlich, Born et al. 2013a) noch mittels NIRS (Born, Holmberg et al. 2014; Born, Zinner et al. 2014) ein gesteigerter Blutfluss oder erhöhte Muskeloxygenierung festgestellt werden. Der blutflusssteigernde Effekt von Kompressionsbekleidung, der in klinischen Studien bei Patienten mit venöser Insuffizienz gezeigt wurde, scheint sich somit nicht in gleichem Maße bei gesunden und trainierten Athlet/innen zu manifestieren oder gar die Erklärung für eine potentielle Leistungssteigerung zu liefern. Vielmehr scheinen kinematische und subjektive Parameter, wie eine veränderte Lauftechnik und verringertes Belastungsempfinden, die intermittierende Sprintleistung verbessert zu haben.

In zukünftigen Untersuchungen wäre es wichtig, die in *Studie 3* gezeigte Leistungssteigerung mit Kompressionsbekleidung in Abhängigkeit variierender Druckstärken zu messen. Anhand der gezeigten Ergebnisse stellt sich die Forschungsfrage, welche Druckstärke die größte Leistungssteigerung während intermittierender Sprintbelastung hervoruft. Weiter wäre interessant zu untersuchen, ob sich die gezeigte Leistungssteigerung während intermittierender Sprintbelastung auch unter Feldbedingungen im Mannschaftssport zeigen lässt. Während Spielsituationen könnten hier Laufweg- und Aktionsanalysen Aufschluss über mögliche ergogene Effekte durch die Applikation von Kompressionsbekleidung geben.

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IV. Methodenanhang

Im Folgenden werden die in *Studie 1, 2* und *3* verwendeten Materialien und Messinstrumente spezifiziert und in alphabetischer Reihenfolge aufgeführt:

Material und Messmethodik	**Parameter**	**Geräte-spezifikation**	**Hersteller**
Amperometrie	- Laktatkonzentration im kapillaren Vollblut [$mmol \cdot L^{-1}$]	EbioPlus	Eppendorf AG Hamburg Deutschland
bioelektrischer Impedanzanalyse	- Körpermasse [kg] - Körperfett anteilig in [%] - Körperfett [kg] - Fettfreie Masse [kg]	Tanita BC 418 MA	Tanita Corp. Tokyo Japan
Druckmessung	- Anpressdruck der Kompressions-bekleidung an verschiedenen Muskelgruppen [mmHg]	SIGaT	Ganzoni-Sigvaris St. Gallen Schweiz

Elektro-myographie	-	Muskelaktivität [iEMG %]	TeleMyo 2400T	Noraxon Inc. Scottdale, AZ USA
	an *m. gluteus maximus, m. rectus femoris, m. vastus lateralis, m. biceps femoris, m. gastrocnemius medialis*			
GPS	-	Geschwindigkeits-messung [$m \cdot s^{-1}$]	MetaMax 3B	Cortex Leipzig Deutschland
Herzfrequenz-messung	-	Herzfrequenz [$s \cdot min^{-1}$]	Polar T31	Polar Electro Oy Kempele Finnland
Kinematische Bewegungs-analyse	- - -	Hüftwinkel [°] Schrittlänge [m] Schrittfrequenz [Hz]	GoPro	GoPro San Mateo, CA USA
			Kinovea (Version 0.8.15)	Kinovea Bordeaux Frankreich

Kompressions-bekleidung		*Studie 2:*	Sigvaris St Gallen Schweiz
		Studie 3:	PUMA SE Herzogenaurach Deutschland
Lichtschranken	- Zeitmessung [min:s]	TDS - 2011	TDS Werthner Sport Consulting Linz Österreich
Nahinfrarot-spektroskopie	- Muskeloxygenierung (Tissue saturation index) [%] - Oxy-hemoglobin [µM·cm] - Deoxy-hemoglobin [µM·cm] - Blutvolumen (Total hemoglobin) [µM·cm] am *m. vastus lateralis*	Portamon	Artinis Medical System Zetten Niederlande
Powermeter	- Leistung [W]	Cyclus2	RBM Elektronik-Automation GmbH Leipzig Deutschland

Spiroergometrie	- Sauerstoffaufnahme [mL·min^{-1}] - Atemminutenvolumen [L·min^{-1}]	MetaMax 3B	Cortex Leipzig Deutschland
Statistik-Software		Statistica (Version 7.1) MedCalc (Version 11.5.1.0)	StatSoft Inc. Tulsa, OK USA MedCalc Mariakerke Belgium
subjektives Belastungs-empfinden	- Borg-Skala (6–20) für *ganzer Körper, Oberschenkel, Waden*		Borg G. (1970). **Perceived exertion as an indicator of somatic stress.** *Scand J Rehabil Med, 2*(2), 92-98.
Thermometer	- Hauttemperatur [°C]	MSR Modular Signal Recorder	Prospective Concepts AG Glattbrugg Schweiz

V. Gesamttexte der *Studien 1, 2* und *3*

1. Born DP, Sperlich B, Holmberg HC. (2013). **Bringing light into the dark: effects of compression clothing on performance and recovery.** *Int J Sports Physiol Perform*, 8(1), 4-18.

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2. Born DP, Zinner C, Herlitz B, Richter K, Holmberg HC, Sperlich B. (2014). **Muscle Oxygenation Asymmetry in Ice Speed Skaters is not Compensated by Compression.** *Int J Sports Physiol Perform*, 9(1), 58-67.

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3. Born DP, Holmberg HC, Goernert F, Sperlich B. (2014). **A novel compression garment with adhesive silicone stripes improves repeated sprint performance – a multi-experimental approach on the underlying mechanisms.** *BMC Sports Sci Med Rehabil*, May 30(6), 21.

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International Journal of Sports Physiology and Performance, 2013, 8, 4-18

INTERNATIONAL JOURNAL OF
SPORTS PHYSIOLOGY
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BRIEF REVIEW

Bringing Light Into the Dark: Effects of Compression Clothing on Performance and Recovery

Dennis-Peter Born, Billy Sperlich, and Hans-Christer Holmberg

To assess original research addressing the effect of the application of compression clothing on sport performance and recovery after exercise, a computer-based literature research was performed in July 2011 using the electronic databases PubMed, MEDLINE, SPORTDiscus, and Web of Science. Studies examining the effect of compression clothing on endurance, strength and power, motor control, and physiological, psychological, and biomechanical parameters during or after exercise were included, and means and measures of variability of the outcome measures were recorded to estimate the effect size (Hedges *g*) and associated 95% confidence intervals for comparisons of experimental (compression) and control trials (noncompression). The characteristics of the compression clothing, participants, and study design were also extracted. The original research from peer-reviewed journals was examined using the Physiotherapy Evidence Database (PEDro) Scale. Results indicated small effect sizes for the application of compression clothing *during* exercise for short-duration sprints (10–60 m), vertical-jump height, extending time to exhaustion (such as running at VO_{2max} or during incremental tests), and time-trial performance (3–60 min). When compression clothing was applied for recovery purposes *after* exercise, small to moderate effect sizes were observed in recovery of maximal strength and power, especially vertical-jump exercise; reductions in muscle swelling and perceived muscle pain; blood lactate removal; and increases in body temperature. These results suggest that the application of compression clothing may assist athletic performance and recovery in given situations with consideration of the effects magnitude and practical relevance.

***Keywords**:* blood flow, cardiac output, heart rate, muscle damage, oxygen uptake, oscillation, venous hemodynamics

In the past 2 decades, various forms of compression clothing have been used by elite and recreational athletes. In running[1,2] and cycling,[3,4] lower body compression clothing such as knee-high socks, shorts, and full-length tights are the most common types of compression garments. To improve hemodynamics, "graduated compression" with pressure decreasing from distal to proximal is recommended.[5] Upper- or full-body compression is applied in various sports to improve maximal strength and power, such as bench-press exercises[6] and throwing performance in cricket players.[7]

The increasing popularity of compression clothing in different sports is likely due to accumulating evidence of enhanced performance[1,8] and recovery.[9–11] Performance in maximal strength and power tasks, such as vertical jumping, has been shown to improve with the application of compression clothing; this is possibly due to increased proprioception and reduced muscle oscillation.[8] However, endurance exercise such as submaximal running seems to be unaffected,[2,12] even if compression clothing has been shown to improve venous hemodynamics[13] and increase deeper-tissue oxygenation[14] and the clearance of metabolites.[15] From a thermoregulatory point of view, compression clothing has been shown to increase muscle temperature,[16] potentially by reducing skin blood flow.[17]

Currently, there has been 1 review summarizing the findings of the application of compression clothing for exercise and recovery, and its conclusions were based mostly on the statistically significant results in the reviewed articles.[18] That review also concludes that there are some isolated indications for physical and physiological effects, including attenuation of muscle oscillation, improved joint awareness, perfusion augmentation, and altered oxygen use at submaximal intensities, whereas the effects of compression clothing on indicators of recovery performance remain inconclusive.

The practical application of statistical significance when comparing the findings of compression and noncompression conditions is open to discussion since it may be influenced by sample size and data variance. By increasing the number of participants, and decreasing variance, statistical significance will be achieved when comparing an experimental and a control trial.[19] Therefore, it seems more relevant to calculate effect sizes

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(ESs) to compare and quantify the various findings and detect the practical meaningfulness of the application of compression clothing. When findings are based on individual studies and transferred to general statements, the focus moves to their practical relevance instead of relying solely on statistical significance.[19] The approach using Hedges *g* was shown to optimize calculation of the ES by using a pooled standard deviation of both groups, hence standardizing mean differences.[20] This quantitative approach has been implemented in other systematic reviews in exercise science.[21–23]

In general, the heterogeneity of test procedures, with differing types and amounts of compression, makes it difficult to perform a comparison between different studies evaluating compression clothing in an athletic population. Our intent was to review the literature to identify possible benefits of compression clothing for performance and recovery.

The aims of this systematic review regarding the application of compression clothing for performance and recovery were to summarize results from existing data; identify the benefits for endurance and strength, as well as power and motor control; quantify effects on physiological, psychological, and biomechanical parameters; identify possible underlying mechanisms for observed results; and provide recommendations for athletes and consumers.

Methods

Data Sources

A computer-based literature research was performed during July 2011 using the electronic databases PubMed, MEDLINE, SPORTDiscus, and Web of Science. In addition, the reference lists from these articles and previously known cases were cross-referenced for further relevant studies. The following key words were used to retrieve pertinent articles: *athlete, balance, blood flow, blood lactate, compression clothing, endurance, exercise, fatigue, garments, heart rate, muscle damage, pain, swelling, oscillation, oxygenation, oxygen uptake, performance, perceived exertion, power, proprioception, recovery, strength, stroke volume, textiles, thermoregulation, time to exhaustion,* and *time trial*.

Study Selection

Peer-reviewed studies were included if they investigated any kind of compression clothing in relation to endurance (n = 15), strength (n = 3), power (n = 8), or both endurance and power (n = 5) during or after exercise. The studies had to assess physiological, biomechanical, or psychological parameters during and/or after exercise. Only studies that presented absolute data as means and measures of variability for the calculation of ESs from an experimental (compression) and a control group (noncompression) were included. Finally, the research must have been conducted on participants without any cardiovascular, metabolic, or musculoskeletal disorders (Figure 1).

Quality Assessment

Each study meeting the inclusion criteria was additionally evaluated with the Physiotherapy Evidence Database (PEDro) Scale by 2 independent reviewers.[24] On the PEDro scale an item answered with "yes" adds 1 point to the score and "no" contributes 0 points, with a maximum of 10 points. This method has been used in previous systematic reviews for the methodological quality assessment of studies.[25–27]

Statistical Analysis

To compare and quantify the various findings of performance and recovery, ESs for each study were determined as proposed by Glass.[28] For each parameter, the ES (Hedges *g*) and associated 95% confidence interval were calculated. Hedges g was computed using the difference between means of an experimental (compression) and control (noncompression) group divided by the average population standard deviation.[20] To optimize ES calculation and estimate the standard deviation for Hedges' g, baseline standard deviations of experimental and control groups were pooled.[20] According to standard practice, the ESs were then defined as trivial (<.10), small (.10–.30), moderate (.30–.50), or large (>.50).[19] All statistical analyses were carried out using MedCalc, version 11.5.1.0 (MedCalc, Mariakerke, Belgium).

Results

Of the initial 423 studies identified, 31 studies were examined using the PEDro score, with an average score of 6.1, ranging from 5 to 9 (maximum possible score = 10 points).

The characteristics of the participants and the compression clothing, measured parameters, and the protocols for each study are summarized in Table 1. The calculated ESs relating to the effects of applying compression clothing for exercise and performance and/or recovery are presented in Figures 2 and 3.

The sample sizes (n = 5–21), age (19–39 y) and gender of the participants (male n = 22, female n = 3, mixed gender n = 5, no gender information n = 1), and type of compression clothing (shirts n = 2, tights n = 14, stockings n = 2, shorts n = 3, knee-high socks n = 9, whole-body compression consisting of tights and a shirt n = 4) that were applied in the reviewed studies showed a high variability (Figure 4). Only 11 studies included elite or well-trained subjects, while 20 included recreational athletes or participants competing at a regional level. Overall, 16 studies used a graduated compression, with pressure decreasing from distal to proximal. Moreover, 19 studies provided data including the amount of exerted pressure ranging from 8 to 40 mmHg, whereas 12 studies reported no data (Table 1).

Exercise and Performance

Altogether, the ES results indicate that compression clothing had either small positive or no effects on performance during exercise. While maximum oxygen uptake was

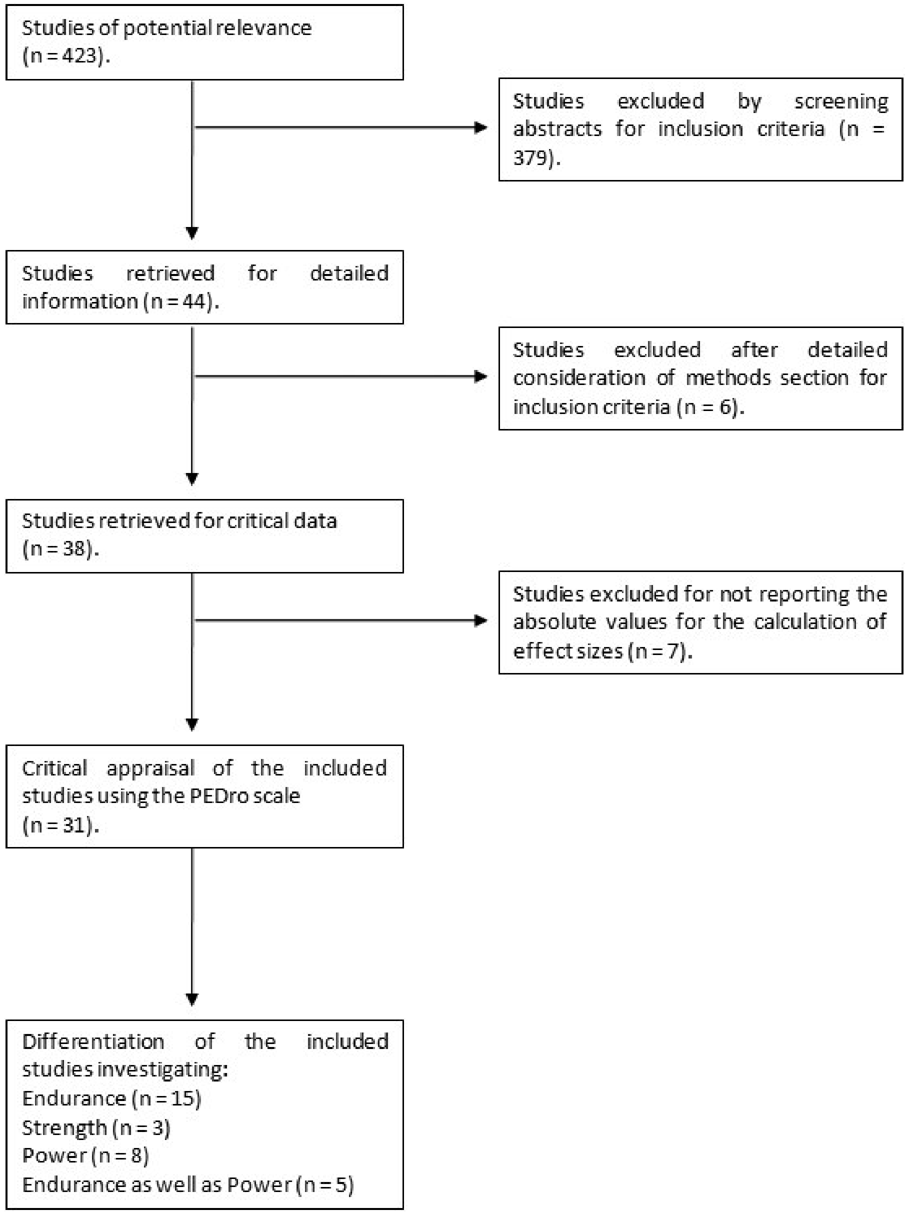

Figure 1 — Process of study selection for the inclusion in the systematic review.

not affected (ES = 0.08, Figure 2),[1,4,15,29–32] performance during maximal endurance exercise such as time to exhaustion (Table 1)[29,31–36] and time-trial performance (3–60 min)[12,15,37] indicated small positive effects (ES = 0.15). In addition, endurance-related parameters such as submaximal oxygen uptake (ES = 0.01),[2,29,32,36,38] blood lactate concentration during continuous exercise (ES = –0.04),[2–4,7,29,31,32,36–40] blood gas such as saturation[2,7,29] and partial pressure of oxygen (ES = 0.01),[7,29] and cardiac parameters including heart rate,[2,32,37,38,40] cardiac output, cardiac index, and stroke volume (ES = –0.08)[2] were not affected by the application of compression compared with noncompression clothing.

Small positive ESs (ES = 0.12, Figure 2) were detected for improvements in single and repeated sprinting (10–60 m),[7,16,30,39,41] as well as vertical jumping (ES = 0.10),[30,37,39,42] in participants wearing compression clothing. Peak leg power measured on a cart dynamometer[16] and performance during maximal-distance throwing[7] were not affected by compression clothing (ES = 0.00). In addition, there were no effects on balance, joint-position sense,[30] or arm tremble during bench press[6] (ES = –0.02).

No mean effects were observed for changes in the perceived exertion during or immediately after exercise (ES = 0.05, Figure 2)[1,7,12,29,37,38,41] when compression clothing was applied.

Table 1 Studies Investigating the Effect of Compression Clothing on Performance and Recovery Enhancement

	Characteristics of Participants		Characteristics of Compression Clothing				
Study	Sample size, gender, age (y)	Athletic category	Type	Applied pressure (mmHg)	Measure	Study protocol (occasion when compression clothing was applied)	Effects of compression clothing
Ali et al[37]	12, M+F, 33 ± 10	Competitive runners (VO_{2max} 68.7 ± 6.2 mL · kg^{-1} · min^{-1})	Socks (G)	15, 21, 32	P, R	10-km TT (during exercise)	TT↔, La↓, CP↑↓, jump↑↓, RPE↑↓,
Dascombe et al[32]	11, M, 28 ± 10	Well-trained runners and triathletes (VO_{2max} 59.0 ± 6.7 mL · kg^{-1} · min^{-1})	Tights (G)	16–22, 14–19	P	Incremental running test and TTE at 90% VO_{2max}. $Temp_{amb}$: 22°C ± 2°C (during exercise)	VO_{2max}↑, TTE↔, VO_2↑↓, La↓, CP↔
Sperlich et al[2]	15, M, 22 ± 1	Well-trained runners and triathletes (VO_{2max} 57.2 ± 4.0 mL · kg^{-1} · min^{-1})	Socks (G)	10, 20, 30, 40	P	45-min treadmill running at 70% of VO_{2max} (during exercise)	VO_2↑↓, La↑↓, CP↑↓, SO_2↑↓, HR↑
Ali et al[38]	10, M, 36 ± 10	High-performance runners and tri-athletes (VO_{2max} 70.4 ± 6.1 mL · kg^{-1} · min^{-1})	Socks (G)	12–15, 23–32	P, R	40-min treadmill running at 80% VO_{2max} (during exercise)	VO_2↑↓, La↑↓, CP↑↓, RPE↑↓, jump↑↓
Cabri et al[40]	6, M, 31 ± 7	Trained runner (5000-m best time 1445 ± 233 s)	Socks		P, R	Submaximal run (5000 m) at a velocity of 85% of the 5000-m best time (during exercise, 2 min after)	La↔, CP↑
Duffield et al[39]	11, M, 21 ± 3	Regional rugby players (3–4 training sessions/wk and 1 game/wk)	Tights	10–30	P, R	Intermittent sprinting: 10 min (1 × 20-m sprint and 10 squat jumps/min; during exercise, 24 h after)	La↑↓, jump↑↓, sprint↑↓, DOMS↑, CK↑↓, damage marker↑↓, HR↔, pH↑
Goh et al[33]	10, M, 29 ± 10	Recreational runners (VO_{2max} 58.7 ± 2.7 mL · kg^{-1} · min^{-1})	Tights (G)	9–14	P	20 min at 1st ventilatory threshold followed by run to exhaustion at VO_{2max} at 10°C and 32°C (during exercise)	TTE↑
Jakeman et al[11]	8, F, 21 ± 2	Physically active (>3 times/wk)	Tights (G)	15–17	R	Intermittent jumping: 10 × 10 drop-jumps (1 jump/10 s) with 1-min rest between sets (compression 12 h after exercise)	CK↑↓
Jakeman et al[48]	8, F, 21 ± 2	Physically active (>3 times/wk)	Tights (G)	15–17	R	Intermittent jumping: 10 × 10 drop-jumps (1 jump/10 s) with 1-min rest between sets (compression 12 h after exercise)	CK↑↓
Kraemer et al[10]	20, M+F, 23 ± 3	Resistance-trained (>2 y)	WBC		R	Barbell resistance-training workout: 8 exercises, 3 × 8–10-RM with 2- to 2.5-min rest between sets (compression 24 h after exercise)	DOMS↑
Rimaud et al[3]	8, M, 27 ± 1	Trained athletes (VO_{2max} 53.3 ± 2.7 mL · kg^{-1} · min^{-1})	Socks (G)	12–22	P	Incremental cycling test (during exercise)	La↓
Sear et al[36]	8, M, 21 ± 1	Team amateur athletes (VO_{2max} 57.5 ± 3.7 mL · kg^{-1} · min^{-1})	WBC		P	45-min high-intensity interval treadmill running (during exercise)	TTE↑, VO_2↑↓, La↑

(continued)

Table 1 *(continued)*

	Characteristics of Participants		Characteristics of Compression Clothing				
Study	Sample size, gender, age (y)	Athletic category	Type	Applied pressure (mmHg)	Measure	Study protocol (occasion when compression clothing was applied)	Effects of compression clothing
Sperlich et al[29]	15, M, 27 ± 5	Well-trained runners and triathletes (VO_{2max} 63.7 ± 4.9 mL · kg^{-1} · min^{-1})	Socks, tights, WBC	20	P	15-min treadmill running at 70% VO_{2max} followed by running to exhaustion at v_{max} of previous incremental test (during exercise)	VO_{2max}↑, TTE↓, VO_2↑↓, La↑↓, pO_2↑↓, SO_2↑↓, RPE↑
Davies et al[43]	11, M+F, 20 ± 1	Netball and basketball, university level	Tights (G)	15	R	Intermittent jumping: 5 × 20 drop-jumps with 2-min rest between sets (compression 48 h after exercise)	Jump↑, sprint↑↓, swelling↔, DOMS↑↓, CK↓, damage marker↑↓
Higgins et al[34]	9, F, 23 ± 5	Elite netball players	Tights		P	Intermittent sprinting and jumping in a simulated netball game (4 × 15 min; during exercise)	TTE↑
Houghton et al[41]	12, M, 21 ± 2	Field hockey, amateur (VO_{2max} 58.6 ± 5.5 mL · kg^{-1} · min^{-1})	Shorts and shirt		P, R	Intermittent sprinting: 20-m sprints in a simulated hockey game (4 × 15 min; during exercise)	Sprint↓, RPE↑↓, HR↓,
Kemmler et al[31]	21, M, 39 ± 11	Moderately trained runners (VO_{2max} 52.0 ± 6.1 mL · kg^{-1} · min^{-1})	Socks (G)	24	P	Incremental treadmill running test (during exercise)	TTE↑, VO_{2max}↑, La↔
Silver et al[6]	5, M, 24 ± 6	Highly strength-trained 1-RM bench press (>125% BW)	Shirt		P	1-RM bench press, quantification of vertical and horizontal bar movements (during exercise)	Motor control↑↓
Duffield et al[16]	14, M, 19 ± 1	Regional rugby players	Tights		P, R	Intermittent sprinting: 10- and 20-m sprints in a simulated rugby game (4 × 15 min), $temp_{amb}$ 16–18°C (compression 18 h after exercise)	Sprint↑, strength & power↑↓, CK↑↓, temp↑
French et al[47]	10, M, 24 ± 3	Recreational/regional soccer and rugby players	Tights (G)	10–12	R	6 × 10 parallel squats at 100% BW + 11th repetition at 1-RM (compression 12 h after exercise)	CK↑↓, damage marker↑↓
Montgomery et al[44]	10, M, 19 ± 2	Regional basketball players training 8–10 h/wk	Tights	18	R	3-day tournament with one 48-min game each day (compression 18 h after exercise)	Jump↑, sprint↓
Montgomery et al[45]	10, M, 19 ± 2	Regional basketball players training 8–10 h/wk	Tights	18	R	3-day tournament with one 48-min game each day (compression 18 h after exercise)	Swelling↑, DOMS↑
Scanlan et al[4]	12, M, 21 ± 4	Amateur cyclists (VO_{2max} 55.2 ± 6.8 mL · kg^{-1} · min^{-1})	Tights (G)	9–20	P	1-h time trial (on cycling ergometer; during exercise)	VO_{2max} ↓, La↑↓

Ali et al[12]	14, M, 22 ± 1	Amateur runners: (1) VO_{2max} 56.1 ± 0.4 mL · kg^{-1} · min^{-1}, (2) VO_{2max} 55.0 ± 0.9 mL · kg^{-1} · min^{-1}	Socks (G)	18–22	P, R	2 × 20-m shuttle-runs (separated by 1 h) and 10-km TT (road run; during exercise)	TT↓, RPE↔, DOMS↔, HR↔,
Duffield et al[7]	10, M, 22 ± 1	Regional cricket players	WBC		P, R	Maximal-distance throwing, throwing accuracy, and intermittent sprinting: 20-m sprints/min for 30 min. $Temp_{amb}$ 15°C ± 3°C (during exercise, 24 h after)	La↑, SO_2↓, pO_2↓, sprint↑↓, strength & power↑, RPE↓, HR↑, pH↓, CK↑, temp↑
Bringard et al[1]	6, M, 31 ± 5	Well-trained runners (VO_{2max} 60.9 ± 4.4 mL · kg^{-1} · min^{-1})	Tights		P, R	Energy cost at 10, 12, 14, 16 km/h ($Temp_{amb}$ 31°C) and 15-min treadmill running at 80% VO_{2max}. $Temp_{amb}$ 23.6°C (during exercise)	VO_{2max}↓, RPE↑, temp↑
Maton et al[35]	15, M, 32 ± 6	Healthy (type of sport not specified)	Stockings (G)	15–21	P, R	Maintaining 50% of 1-RM ankle dorsiflexion to exhaustion (during exercise, 10 min after)	TTE↓, strength & power↑
Trendell et al[46]	11, M, 21 ± 3	Recreational athletes (type of sport not specified)	Stockings (G)		R	30-min downhill treadmill walking (6 km/h, 25% grade; compression 48 h after exercise)	DOMS↑, damage marker↑↓
Bernhardt et al[30]	13, M+F, 26 ±	Healthy active students (type of sport not specified)	Shorts		P, R	Active range of motion, agility test, balance test, joint-angle replication; 20-m sprint, vertical jump; 20-m shuttle run (during exercise)	VO_{2max}↔, jump↔, sprint↑, motor control↓
Kraemer et al[42]	18, M+F, 21 ± 3	University volleyball players	Shorts		P	10 consecutive countermovement jumps (during exercise)	Jump↑↓
Berry et al[15]	6, M, 23 ± 5	Well-trained: (1) VO_{2max} 52.8 ± 8.0 mL · kg^{-1} · min^{-1}, (2) VO_{2max} 59.9 ± 6.8 mL · kg^{-1} · min^{-1}	Socks (G)	8–18	P	Incremental treadmill running test to determine VO_{2max} and 3 min at 110% VO_{2max} (on cycling ergometer; during exercise)	VO_{2max}↑, TT↔

Abbreviations: M, male; F, female; VO_2, oxygen uptake; G, graduated; P, performance; R, recovery; TT, time trial; ↔, no effect from compression; La, blood lactate concentration; ↓, negative effect from compression; CP, cardiac parameters (HR, cardiac output, cardiac index, stroke volume); ↑↓, contradictory results: positive, as well as negative, effects from compression; RPE, rating of perceived exertion; $temp_{amb}$, ambient temperature; ↑, a positive effect from compression; TTE, time to exhaustion; SO_2, oxygen saturation; HR, heart rate; jump, vertical-jump exercise; Sprint, short-duration sprinting; DOMS, delayed onset of muscle soreness; CK, creatine kinase; damage marker, additional muscle damage marker; WBC, whole-body compression; 1-RM, 1-repetition maximum; pO_2, oxygen partial pressure; Swelling, muscle swelling; strength & power, strength and power exercise; temp, body temperature; BW, body weight.

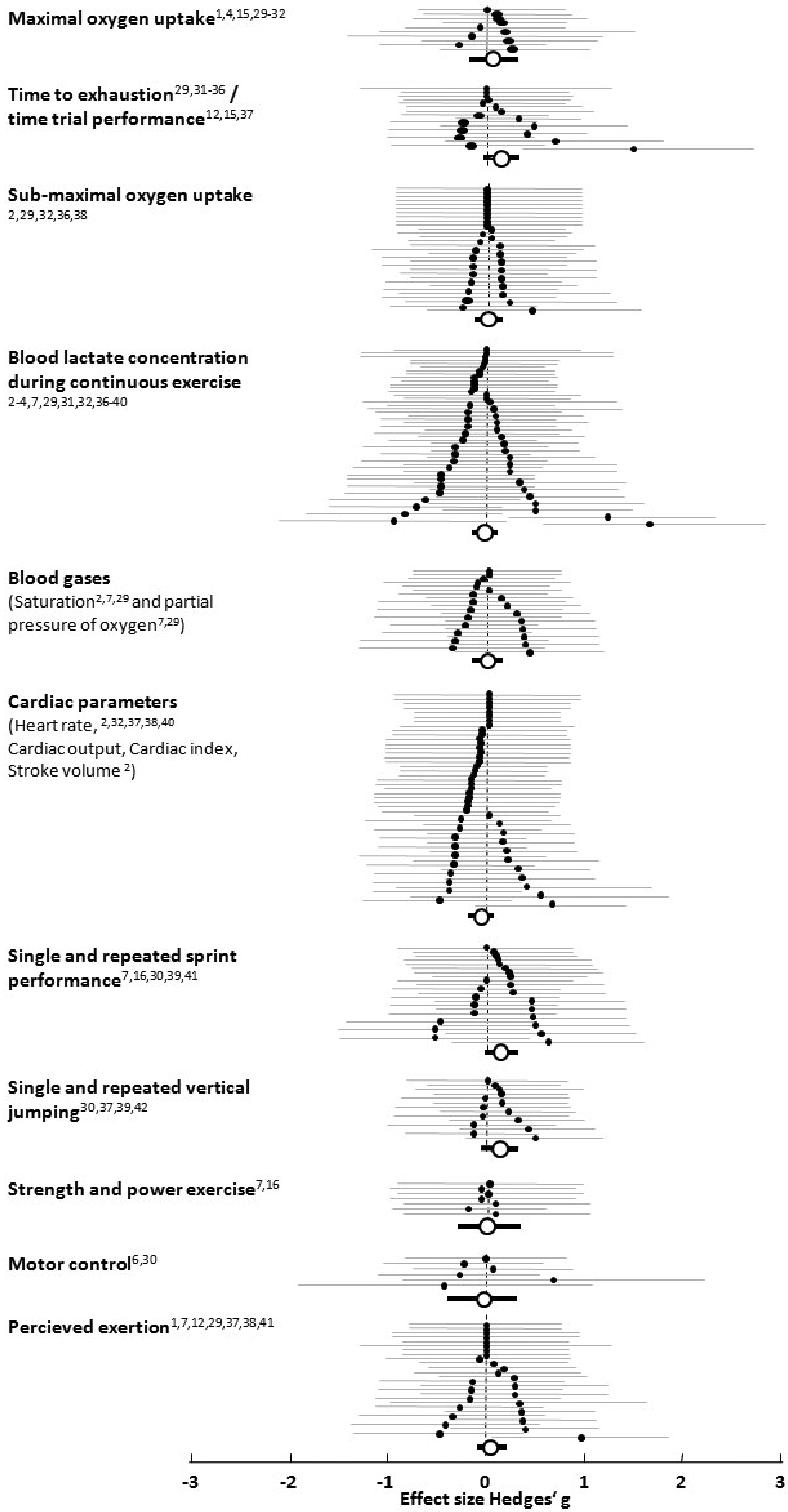

Figure 2 — Effect sizes of the application of compression clothing on performance enhancement.

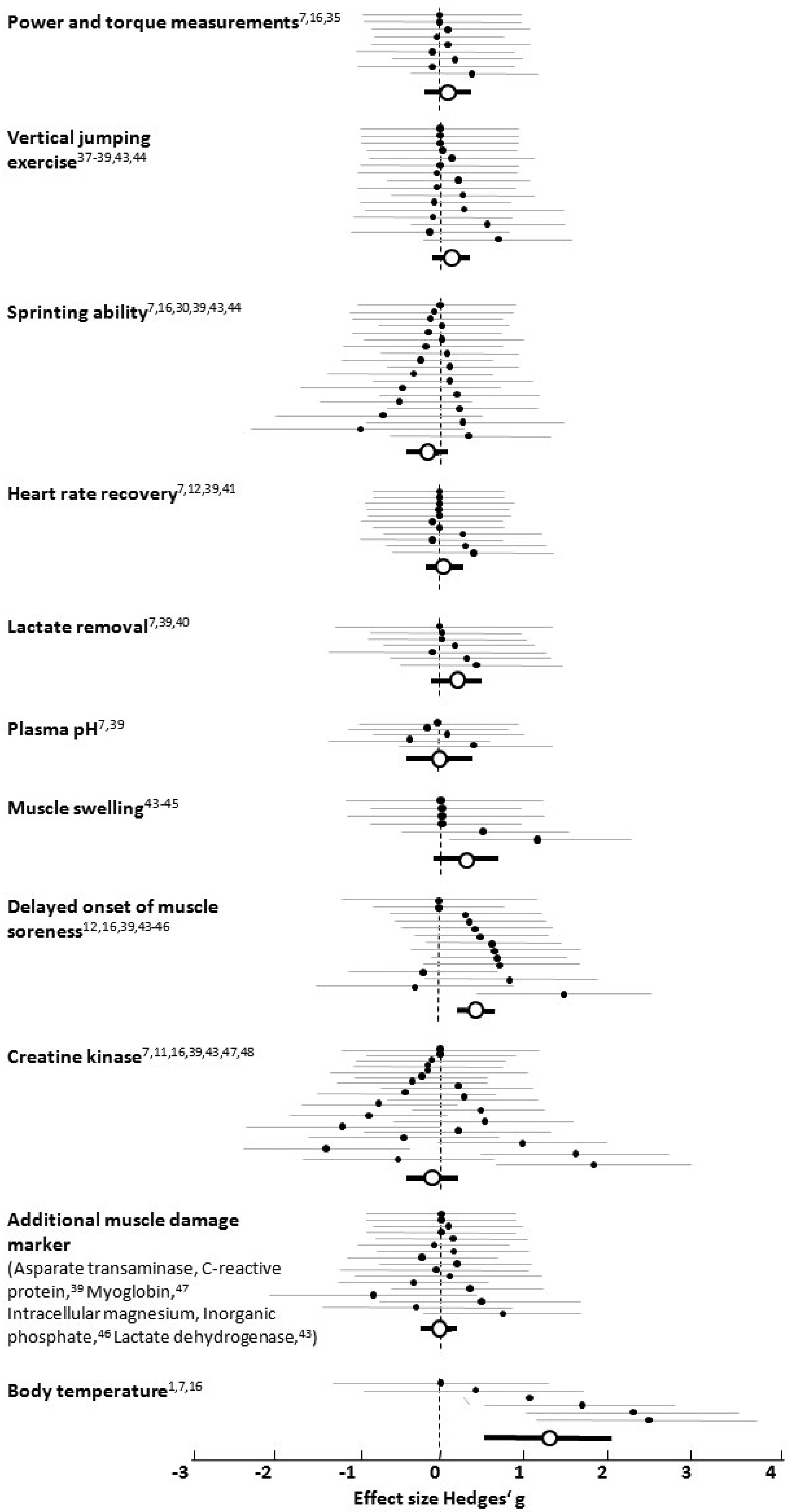

Figure 3 — Effect sizes of the application of compression clothing on recovery enhancement.

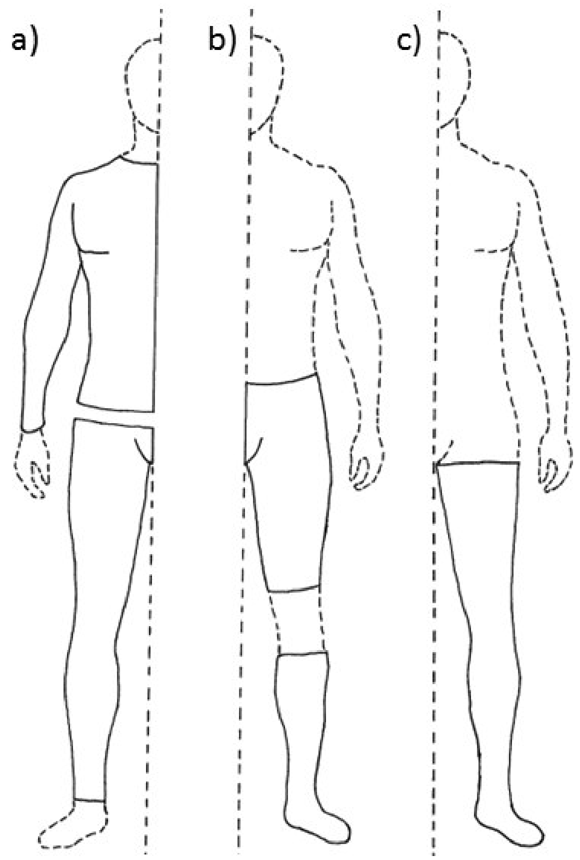

Figure 4 — Different types of compression applied in the 31 studies: a) shirt (n = 2), tights (n = 14), and whole-body compression (n = 4); b) shorts (n = 3) and knee-high socks (n = 9); and c) stockings (n = 2).

Recovery

The current analysis revealed small positive effects on recovery of strength and power tasks (ES = 0.10) such as peak leg power on a cart dynamometer,[16] maximal-distance throwing,[7] and isolated plantar flexion.[35] When applying compression compared with noncompression clothing, recovery of vertical-jump performance was also positively affected (ES = 0.13, Figure 3).[37–39,43,44] However, the recovery of short-sprint ability (10–60 m) was negatively affected by the use of compression clothing (ES = –0.13).[7,16,30,39,43,44]

The application of compression clothing had no effect on heart-rate recovery (ES = 0.07, Figure 3).[7,12,39,41] On the other hand, our analysis discovered small effects on postexercise lactate removal (ES = 0.20),[7,39,40] although there was no effect on plasma pH (ES = 0.02).[7,39]

Recovery-related parameters showed a moderate effect on the reduction of muscle swelling (ES = 0.35, Figure 3)[43–45] and delayed onset of muscle soreness (ES = 0.47)[12,16,39,43–46] when compression clothing was worn for 12 to 48 hours after exercise. Small negative effects regarding muscle-damage markers were detected for levels of creatine kinase (ES = –0.10),[7,11,16,39,43,47,48] and no effects for other myocellular proteins were found (ES = –0.01).[39,43,46,47]

Body temperature was highly affected by the use of compression clothing, with large increases (ES = 1.38, Figure 3) during and after intermittent high-intensity exercise (15–18°C)[7,16] and submaximal running (23–31°C).[1]

Discussion

The ES calculations indicated small ESs for the application of compression clothing *during* exercise for improving short-duration sprints (10–60 m), vertical-jump height, and time to exhaustion (such as running at VO_{2max} or during incremental tests), as well as time-trial performance (3–60 min). When compression clothing was applied for recovery purposes 12 to 48 hours after exercise, small or moderate effects were also observed for recovery of maximal strength and power performance, recovery of vertical-jump performance, blood lactate removal, reductions in muscle swelling and perceived muscle pain, and increased body temperature.

It is worth mentioning that compression clothing is also used by individuals who run but suffer from medial tibial stress syndrome, for example (a common running injury), or by individuals who suffer from chronic venous insufficiency. Therefore, the current results based on healthy individuals may not be the same in injured and unhealthy individuals who practice sports.

Endurance Exercise

While previous research concluded that there is some evidence that submaximal oxygen use is altered by the application of compression clothing,[18] our ES calculation cannot confirm those findings in general. Based on the average ES calculations, none of the physiological markers during exercise, such as oxygen uptake, blood lactate concentration during continuous exercise, blood gases, or cardiac parameters, were affected (Figure 2).

However, 7 studies that evaluated time to exhaustion and 3 examining time-trial performance demonstrated positive effects attributed to the application of compression clothing. It has been shown that time-to-exhaustion tests are less reliable (coefficient of variation >10%) than constant-duration tests such as time trials (coefficient of variation <5%),[49] which may explain why these findings are not in line with the possible underlying physiological markers. Since it is difficult to create a placebo condition for compression clothing, it cannot be excluded that extended time to exhaustion is due to improved perceptions and a result of the participants' intuitions of expected findings.[12] But the overall sensation of vitality plays a crucial role in exercise performance,[50] and any changes in perceived exertion during exercise may serve as an ergogenic aid for improving performance regardless of potential physiological effects.[7]

Earlier research has recommended applying graduated compression clothing, with pressure decreasing continuously from distal to proximal to improve hemodynamics.[5] Due to the various differences in leg dimensions among a given population, it was recommended that compression clothing be custom made and individually fitted to have a proper amount of pressure on the various parts of the limbs.[43] None of the reviewed studies indicated the use of custom-made compression clothing, and 17 of 31 studies applied graduated compression. Therefore, the lack of effects on physiological parameters such as oxygen uptake or cardiac parameters might partly be due to insufficient or inappropriate compression properties of the applied compression clothing.

Strength and Power Exercise

While MacRae et al[18] reported mixed results for jumping performance and that sprinting was unaffected by the application of compression clothing, our ES calculation revealed small positive effects on single and repeated sprint performance and vertical jumping. Repeated-sprint ability, and short-duration sprints separated by short recovery periods, was shown to rely on metabolic and neuronal factors such as H^+ buffering, oxidative capacity, muscle activation, and muscle-fiber-recruitment strategies.[51] Since our ES calculation indicated positive effects on lactate removal after and between bouts of high-intensity exercise, the application of compression clothing seems to aid performance and recovery. It is suggested that hemodynamic and neuronal mechanisms such as improved venous return,[5,13,52] enhanced arterial inflow,[53] altered muscle-fiber-recruitment patterns,[1,50] and altered proprioception[54,55] account for these performance improvements (Figure 5).

Venous Return. The blood is driven through the vascular system by the propulsive force of each heartbeat, with the blood pressure being almost zero when the blood enters the venous system. In addition, gravity creates a hydrostatic force of 80 to 100 mmHg in an upright body position that counteracts venous return.[56] Since unidirectional valves are located in the veins, the blood is directed toward the heart with each muscle contraction of the peripheral limbs due to compression on the veins. In shifting superficially located blood to the deeper venous system,[5] the application of compression clothing supports the valve system and aids venous hemodynamics.[5,13,52]

Improved venous hemodynamics have been suggested to result in increased end-diastolic filling of the heart, increasing stroke volume and cardiac output.[12] Since stroke volume is a limiting factor for performance,[57] the application of compression clothing could serve as an ergogenic aid. In this context, Sperlich et al[2] applied 0, 10, 20, 30, and 40 mmHg of sock compression to the calf muscles of runners and reported no changes in cardiac output, cardiac index, or stroke volume. From these knee-high-sock compression data, it remains questionable whether the improved venous hemodynamics (stimulated by a fairly low area of compressed calf muscles) will affect central circulatory and cardiac parameters such as stroke volume and heart rate. However, the application of compression clothing may enhance removal of metabolites and supply of nutrients,[58] which is in line with the findings of the ES calculation showing improved lactate removal (Figure 3).

Arterial Inflow. Similar to the improvements in venous hemodynamics, the application of compression clothing was shown to improve arterial inflow to forearm muscles.[53] This improvement was associated with enhanced local blood flow and improved oxygen delivery and muscle oxygenation.[14] In general, the diameter of the arteries and arterioles is influenced by changes in the transmural pressure gradient.[59] The so-called myogenic response provides a constant blood flow in the precapillary vessels with each heartbeat pumping blood into the circulation. As the pressure of the compression clothing is transmitted into the deeper underlying tissue,[60] the vessels' transmural pressure gradient decreases.[61] The myogenic response of the arteries and arterioles leads to vasodilatation and favors arterial inflow to the muscle, hence increasing local blood inflow.[53]

In supporting venous[5,13,52] and arterial blood flow,[53] the wearing of compression clothing was associated with increased clearance of metabolites and supply of nutrients.[58] Since repeated-sprint ability relies on metabolic factors such as H^+ buffering and oxidative capacity, the application of compression clothing could serve as an ergogenic aid.[51] The ES calculation supports this in showing positive effects of the use of compression clothing on lactate removal during high-intensity exercise. Therefore, compression clothing may improve performance, especially during high-intensity exercise, by supporting hemodynamics.

Neural Mechanisms. Power production, especially short-duration sprints, relies on neural factors such as muscle activation and recruitment strategies.[51] Compression clothing has been linked to improved proprioception, which is the awareness of the body segments and position in space, allowing the individual to know the direction, acceleration, and speed of the limbs during movement.[62] Sensory feedback is provided by mechanoreceptors located in the skin, muscles, ligaments, joint capsules, and connective tissue.[62] It has been shown that the activation of these receptors reduces presynaptic inhibition,[63,64] thus increasing sensory feedback.[30] The use of compression clothing most likely activates the mechanoreceptors in the superficial tissues, enhances sensory feedback,[65] and improves proprioception.[54,55] Since neural factors such as muscle activation and muscle-fiber-recruitment strategies influence power production,[51] improved proprioception from the application of compression clothing corresponds with the ES calculation showing positive effects on short-sprint ability and vertical-jump exercise.

Mechanical Properties. It has been shown that compression clothing decreases oscillatory displacement of the leg muscles during vertical jumping[8,50] and reduces the number of recruited muscle fibers as detected by a decrease in myoelectric activity.[66] Therefore, decreased energy expenditure during submaximal running,[1] delayed

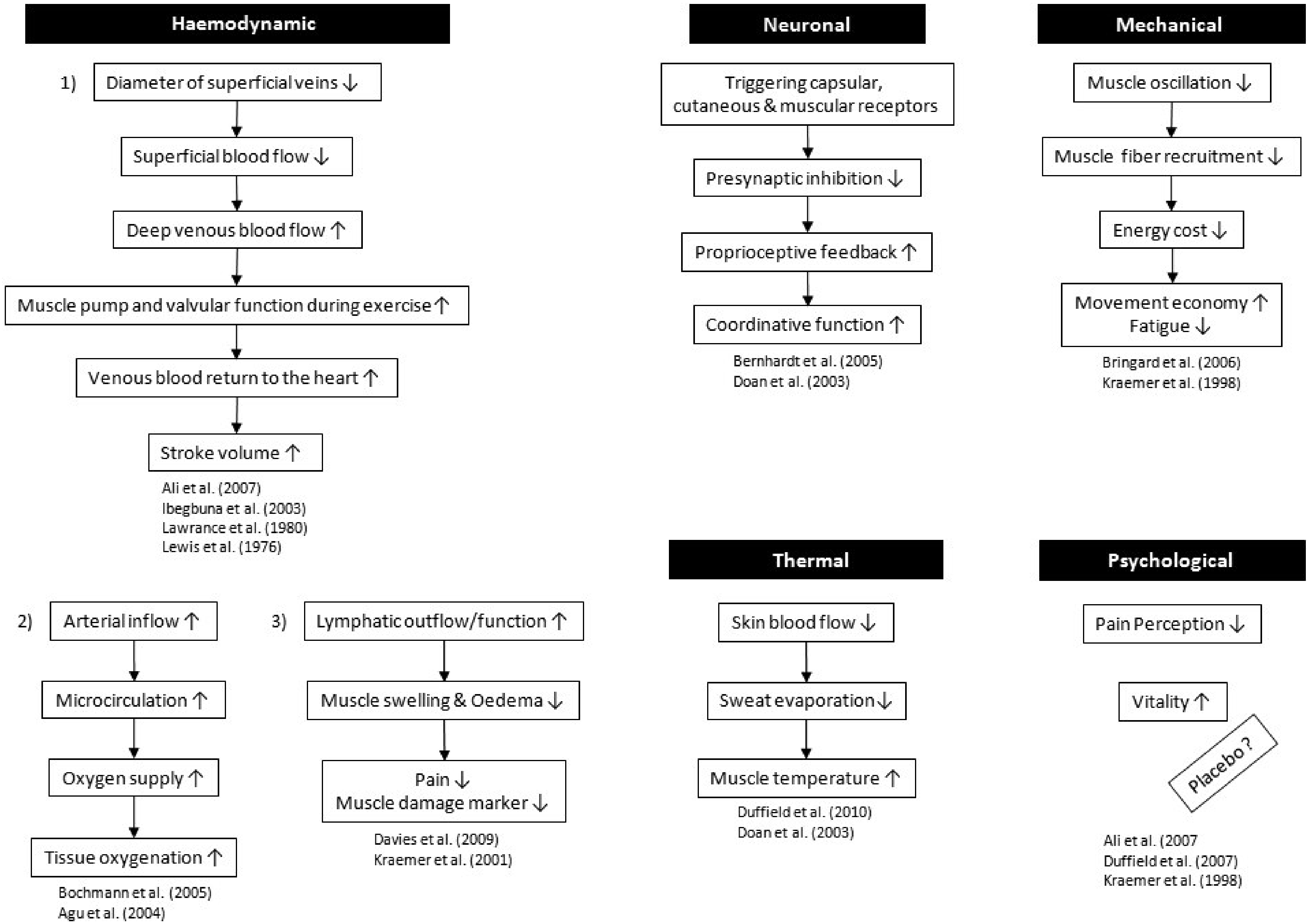

Figure 5 — Biological and psychological mechanisms underlying the application of compression clothing.

fatigue during repetitive vertical-jump exercise,[50] and reduced structural damage during intermittent sprinting[39] were related to decreased oscillatory displacement of the leg muscles by the application of compression clothing. In this case, a fairly high amount of pressure seems to be necessary to reduce the oscillatory displacement. Since only 20 of 31 of the reviewed studies indicated the amount of applied pressure, it is difficult to conclude the optimal amount of pressure for certain exercise modes. Future research is needed to clarify the optimal amount of pressure exerted by compression clothing to reduce oscillatory displacement without negatively affecting hemodynamics.

Recovery 24 to 48 Hours After Exercise

The ES calculation confirms the findings of earlier research[18] concluding an improved recovery of various power and torque measurements with the application of compression clothing 24 to 48 hours after fatiguing exercise. Although jumping exercise was not affected in a previous analysis,[18] our ES calculation showed an improved recovery of vertical jumping (ES = 0.10). These findings may be explained by other physiological markers such as reductions in muscle swelling (ES = 0.35), delayed onset of muscle soreness (ES = 0.47), and increased body temperature (ES = 1.38). Most studies that investigated the effect of compression on recovery applied compression clothing during and/or after exercise. Applying compression exclusively during continuous exercise did not show any benefits for recovery 24 hours after exercise.[38] Therefore, it seems essential to wear compression clothing for at least 12 to 24 hours after exercise to improve recovery.

MacRae et[18] concluded that compression garments produced mixed results for markers of muscle damage and inflammation, as well as immediate and delayed onset of muscle soreness. The current ES calculation revealed negative effects on levels of creatine kinase (ES = –0.10) but no effect on other myofibrillar proteins through the application of compression clothing (ES = –0.01). However, the reduction in muscle soreness 24 to 48 hours after exercise showed medium positive effects (ES = 0.47) with the use of compression clothing. The application of compression clothing was suggested to improve recovery after muscle-damaging exercise protocols by enhancing lymphatic outflow, thus reducing postexercise muscle swelling and pain[67] (Figure 5). Furthermore, increased arterial inflow[14,53] and venous return[5,13,52] were associated with increased clearance of cellular waste products, potentially enhancing cellular repair processes.[43,46]

Lymphatic Outflow. Especially after high-intensity exercise, muscle pain and swelling can occur due to structural damage to the contractile elements of the muscles.[68,69] The following necrosis of the damaged muscle cells and the infiltration of neutrophil cells (immune cells) result in an inflammatory response.[68] Furthermore, the proteins of the damaged contractile elements are released into the interstitial fluid, contributing to elevated tissue osmotic pressure.[67] To equalize the osmotic gradient, fluid from the circulatory system is absorbed, which increases the interstitial fluid and intracompartmental pressure, resulting in edema.[67]

Applying compression clothing may reduce exercise-induced edema by promoting lymphatic outflow and transporting the profuse fluid from the interstitium of the muscle back into the circulation.[67,70] Thereby, intracompartmental pressure is reduced, decreasing pain[67] and serving as a nonpharmaceutical treatment of edema after high-intensity exercise in trained athletes.[10]

It remains unclear why the removal of muscle-damage markers such as creatine kinase was negatively affected, whereas other muscle-damage markers such as lactate dehydrogenase were unaffected. Nevertheless, these enzymes serve as global markers for damage to contractile elements and act as indicators of recovery rather than providing evidence for its progress.[71,72]

Thermoregulation. The application of compression clothing showed a large positive effect on body temperature (ES = 1.38). In general, clothing by itself imposes a physical barrier to heat transfer and hinders sweat evaporation from the skin by representing a layer of insulation.[73]

In this context, an interaction between muscle blood flow and skin and muscle temperature has been reported,[74] and compression clothing has been shown to diminish skin perfusion.[17] This imposition results in a reduction of the thermoregulatory effects of sweat evaporation in addition to the insulating properties of the garment. While the elevated muscle temperature induced by compression clothing might be positive for recovery purposes, the rise in muscle temperature beyond optimal may inhibit performance during endurance exercise in hot environments.[7,8] However, 2 of 3 included studies on compression clothing assessed in this review were performed in moderate environmental conditions (15–18°C).[33,36] Under these conditions, the reduction in evaporation is suggested to be less important while there is an increased reliance on conduction, as well as convection, which does not result in impaired performance.[39] So far, no study has investigated the effect of compression clothing in winter sports. Since the reduction in skin blood flow would increase blood volume in the working muscles, compression might especially serve as an ergogenic aid in performance in cold environmental conditions. Therefore, compression clothing can be applied with cognizance of the underlying atmospheric conditions and duration of the exercise.

Practical Application and Conclusion

Based on our ES calculations summarizing the findings of 31 studies independent of statistical significance, compression clothing promotes numerous physiological processes capable of assisting athletic performance and subsequent recovery. However, in some cases there is little evidence to support some of the purported benefits, and gaps in knowledge are still evident. The magnitude of the effects should also be taken into account when assessing the meaningfulness and practical relevance of the use of compression clothing in a given situation. Based on our ES calculation, we conclude that there are beneficial effects of compression clothing, especially during intermittent high-intensity exercise such as repeated sprinting and jumping, rather than during submaximal endurance exercise. Furthermore, the benefits of compression clothing seem to be most pronounced when it is applied for recovery purposes 12 to 48 hours after significant amounts of muscle-damage-inducing exercise.

Most of the reviewed studies applied lower body compression (ie, knee-high socks, shorts, or tights) with and without distal-to-proximal pressure gradient for performance enhancement. Based on our findings, we conclude that the application of compression clothing during exercise has small effects on improving short-duration sprints (10–60 m), vertical-jump height, and time to exhaustion (such as running at VO_{2max} or during incremental tests), as well as time-trial performance (3–60 min). The use of upper body compression may be of practical relevance to support upper body exercise; however, further research is warranted on this topic. Since several sports regulate their athletes' competition outfit, we recommend the application of lower and upper body compression according to the regulations, nature of sport, and environmental conditions.

If compression clothing is worn for recovery purposes 12 to 48 hours after exercise, we conclude small or moderate effects for recovery after maximal strength and power, particularly vertical-jump exercise; reductions in muscle swelling and perceived muscle pain; and blood lactate removal. Large effects are evident for increased body temperature.

Acknowledgments

The authors declare no conflicts of interest that are directly related to this article. For the preparation of this article, no sources of funding were used for assistance.

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International Journal of Sports Physiology and Performance, 2014, 9, 58-67
http://dx.doi.org/10.1123/IJSPP.2012-0210

INTERNATIONAL JOURNAL OF SPORTS PHYSIOLOGY AND PERFORMANCE
www.IJSPP-Journal.com
ORIGINAL INVESTIGATION

Muscle Oxygenation Asymmetry in Ice Speed Skaters: Not Compensated by Compression

Dennis-Peter Born, Christoph Zinner, Britta Herlitz, Katharina Richter, Hans-Christer Holmberg, and Billy Sperlich

Purpose: The current investigation assessed tissue oxygenation and local blood volume in both vastus lateralis muscles during 3000-m race simulations in elite speed skaters on ice and the effects of leg compression on physiological, perceptual, and performance measures. ***Methods:*** Ten (6 female) elite ice speed skaters completed 2 on-ice trials with and without leg compression. Tissue oxygenation and local blood volume in both vastus lateralis muscles were assessed with near-infrared spectroscopy. Continuous measures of oxygen uptake, ventilation, heart rate, and velocity were conducted throughout the race simulations, as well as blood lactate concentration and ratings of perceived exertion before and after the trials. In addition, lap times were assessed. ***Results:*** The investigation of tissue oxygenation in both vastus lateralis muscles revealed an asymmetry ($P < .00$; effect size = 1.81) throughout the 3000-m race simulation. The application of leg compression did not affect oxygenation asymmetry (smallest $P = .99$; largest effect size = 0.31) or local blood volume ($P = .33$; 0.95). Lap times ($P = .88$; 0.43), velocity ($P = .24$; 0.84), oxygen uptake ($P = .79$; 0.10), ventilation ($P = .11$; 0.59), heart rate ($P = .21$; 0.89), blood lactate concentration ($P = .82$; 0.59), and ratings of perceived exertion ($P = .19$; 1.01) were also unaffected by the different types of clothing. ***Conclusion:*** Elite ice speed skaters show an asymmetry in tissue oxygenation of both vastus lateralis muscles during 3000-m events remaining during the long gliding phases along the straight sections of the track. Based on the data, the authors conclude that there are no performance-enhancing benefits from wearing leg compression under a normal racing suit.

Keywords: aerobic exercise, blood flow, garments, tissue saturation index, venous return, NIRS

In a 3000-m ice speed skating event, athletes complete 7.5 rounds at velocities up to 13 m/s, with international races lasting about 4 minutes. Isometric contractions of the quadriceps femoris muscles[1,2] with intramuscular blood-flow restriction involving anaerobic energy supply[3] and high levels of blood lactate[4] result from the high centrifugal forces during each curve, the low sitting posture, and the long gliding phases.[5]

Assessing metabolic and circulatory responses at the local muscular level in addition to systemic changes such as oxygen uptake and blood lactate concentration is crucial in providing important information for race and conditioning strategies. In this context, near-infrared spectroscopy (NIRS) has previously been applied to investigate changes in local muscle oxygenation and blood volume during speed skating[3,4] and other endurance events such as running[6–8] and cycling.[9,10] For instance, in elite short-track speed skaters, a remarkable asymmetry in oxygenation and blood volume between each the 2 legs' quadriceps femoris muscles was demonstrated during a 500-m race simulation while applying NIRS.[3]

This phenomenon was most pronounced in the long gliding phase when traveling along the apex of the curve in the "hang" position. This involves prolonged static 1-legged contractions in the right leg and leads to a remarkable restriction in blood flow.[3] To minimize wind resistance and maximize leg push-off, athletes in long-track speed skating have to tolerate a deep crouched skating position[11] that involves a remarkable restriction of blood flow due to the high intramuscular forces.[4,12] Since the maintenance of a high step rate when curving in long-track speed skating is an important factor for performance,[13] inducing less static contractions than reported in short-track speed skating, it can be questioned whether the asymmetry in oxygenation and blood volume of quadriceps femoris muscles exists during the curves of a 3000-m ice speed-skating event and remains during the long gliding phases along the straight sections of the track.

A practical option for reducing the asymmetry of oxygenation and blood volume may derive from the application of leg compression. It has been shown that compression clothing supports hemodynamics[14,15] by enhancing venous return via the muscle pump system.[16,17] Even under exercise conditions with an effective muscle pump support,

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compression clothing improved regional blood flow that was accompanied by reduced heart rate and attributed to an enhanced venous flow at high exercise intensities.[18] Other studies showed enhanced muscle oxygenation during high-intensity running[19] and cycling[20] with the application of compression clothing but did not report any changes in local blood flow. Therefore, it remains unclear whether the application of compression clothing can improve local or central hemodynamics in elite ice speed skaters during an all-out effort. Furthermore, the application of compression clothing was demonstrated to enhance clearance of blood lactate concentration, accelerate oxidation of metabolites,[21,22] reduce oxygen uptake,[23] and improve perception,[24–27] but whether compression clothing can enhance endurance performance is a subject of debate.[28]

Since an asymmetry in the muscle oxygenation and blood volume of quadriceps femoris muscles in short-track speed skating is evident[3] and compression has been shown to enhance local peripheral circulation, it is a viable assertion that the muscle oxygenation and blood volume in both quadriceps femoris muscles may be improved by compression and contribute to enhanced 3000-m performance. Even if muscle oxygenation is expected to be lower in the right leg, especially during cornering, we applied compression to both legs to avoid disturbing proprioception and skating technique. Therefore, the purpose of the current study was to investigate whether the application of compression to both legs in elite ice speed skaters improves muscle oxygenation and blood volume, thereby lessen the oxygenation asymmetry in both quadriceps femoris muscles; improves oxygen uptake and ratings of perceived exertion; decreases blood lactate concentration; and, finally, reduces 3000-m time.

Methods

Participants

Ten elite German ice speed skaters (6 women, 4 men) participated in the study (age 23 ± 7 y, body height 173 ± 10 cm, body mass 68.2 ± 13.9 kg, peak oxygen uptake 58 ± 5.2 mL · kg^{-1} · min^{-1}), which was approved by the ethics committee of the University of Wuppertal and in accordance with the declaration of Helsinki. All subjects gave their written consent for participation in the study and were routinely familiar with the laboratory exercise procedures. They were asked to report to all tests well hydrated and to have refrained from alcohol, caffeine, and strenuous exercise for at least 24 hours before testing.

All participants were members of either the German and Dutch national or West German all-star team. A minimum of 8 training years and experience in international competitions was required to participate in the study. The participants' anthropometric data and personal-best times are documented in Table 1.

Experimental Design

All athletes were tested on 3 occasions involving 2 on-ice race simulations carried out with and without leg compression in a randomized order and 1 cycle ramp test for the determination of peak oxygen uptake. All tests were separated by at least 1 week, to guarantee sufficient recovery, and were carried out 1 week after the most important race of the season. The on-ice measurements were performed on a 400-m outdoor track matching the standards for international competitions, and all athletes performed both on-ice trials under similar atmospheric conditions (temperature –1 to –3°C, relative humidity 50–65%), assuming that ice-skate friction was comparable between the events.

After athletes' normal warm-up routines, they were asked to complete the 3000-m in the fastest time possible by applying their individual pacing strategy. During the race, all lap times were recorded and verbal feedback was given to the athletes to ensure competition-like conditions. Using a portable breath-by-breath analyzer (Metamax 3B, Cortex, Leipzig, Germany), gas-exchange data, heart rate (Polar T31, 1Hz, Polar Oy, Kempele, Finland), and global positioning system–based velocity (GPS, 1Hz, Cortex, Leipzig, Germany) were recorded continuously. Muscle oxygenation and muscle blood volume in both

Table 1 Participants' Anthropometric Characteristics and Personal-Best Times, Mean ± SD (range)

Characteristic	All participants (N = 10)	Female (n = 6)	Male (n = 4)
Age, y	23 ± 7 (15–36)	21 ± 4 (16–25)	27 ± 9 (15–36)
Body height, cm	173 ± 10 (161–192)	168 ± 6 (161–174)	181 ± 10 (169–192)
Body mass, kg	68.2 ± 13.9 (52–93.8)	60.5 ± 7.3 (52–69.7)	79.8 ± 13.7 (61.1–93.8)
Body mass index, kg/m^2	22.4 ± 2.1 (20.1–25.6)	21.3 ± 1.3 (20.1–23.3)	24.2 ± 1.9 (21.4–25.6)
Body fat, %	17.8 ± 3.8 (11.8–24.7)	19.8 ± 3.3 (14.9–24.7)	14.9 ± 2.3 (11.8–17.3)
Lean body mass, kg	56.2 ± 12.3 (41.4–77.6)	48.6 ± 6.1 (41.4–54.8)	67.7 ± 10 (53.9–77.6)
Fat mass, kg	12.0 ± 2.9 (7.2–16.2)	12.0 ± 2.5 (9.3–14.9)	12.1 ± 3.8 (7.2–16.2)
VO_{2peak}, mL · kg^{-1} · min^{-1}	58.0 ± 5.2 (49.9–64.5)	57.8 ± 5.9 (49.9–64.5)	58.2 ± 5.3 (51.5–63.9)
Personal-best 3000-m time, min:s	4:38.47 ± 0:26.05 (3:54.13–5:22.45)	4:54.53 ± 0:17,15 (4:30.31–5:22.45)	4:14.38 ± 0:15,98 (3:54.13–4:27.90)

left and right vastus lateralis muscles were determined by a wireless NIRS device (Portamon, Artinis Medical System, Zetten, The Netherlands). Before, directly after, and 10-minute and 30-minute postrace blood samples were collected from the right earlobe for later analysis of blood lactate concentration. Ratings of perceived exertion for the right and left calf, as well as thigh muscles and whole body, were obtained before and immediately after each race simulation using the Borg 6-to-20 scale.[29]

On a third occasion the participants' body composition was determined using 4-electrode bioimpedance analysis (Tanita BC 418 MA, Tanita Corp, Tokyo, Japan) allowing the subsequent assessment of body weight and fat mass. Peak oxygen uptake was assessed in a ramp-test protocol with each athlete's road bike installed in an ergometric appliance (Cyclus2, RBM Elektronik-Automation GmbH, Leipzig, Germany). After a warm-up at 1.2 W/kg the workload increased by 25 W every 30 seconds until voluntary exhaustion was experienced. Heart rate and oxygen consumption were monitored continuously. The highest values of heart rate and oxygen uptake reached during the last 30 seconds of the ramp test were defined as peak heart rate and peak oxygen uptake.

Compression Clothing

For the compression trial all participants wore individually fitted leg compression covering the leg from the ankle to the waist, worn under their normal racing suit. The compression material consisted of 94% polyamide and 6% Lycra. The level of compression was checked 3-fold with a pneumatic sensor (SIGaT, Ganzoni-Sigvaris, St Gallen, Switzerland) before the 3000-m race according to international recommendations.[30] The pressure between the skin and the garment was determined at the calves' and thighs' maximum girth as reported previously.[31,32]

Data Measurement

After the determination of skinfold thickness with a Harpenden caliper (British Indicators Ltd, West Sussex, UK) 2 small, wireless lightweight NIRS devices (weight 85 g, dimensions 83 × 52 × 20 mm) were attached to the subject's left and right vastus lateralis muscles for the measurement of alterations in tissue concentrations of oxyhemoglobin (HbO_2), deoxyhemoglobin (HHb), and total hemoglobin (tHb). The sensors were positioned across the maximum girth of the muscle's belly, midway between the lateral femoral epicondyle and the greater trochanter of the femur, and secured with an adhesive patch without disturbing the subject's normal movement pattern. None of the athletes reported discomfort or distress due to the placement of the equipment. Since the muscle oxygenation of the quadriceps muscle shows a nonuniform pattern,[33,34] the precise placement of the sensor for the subsequent tests was crucial, so the placement of the NIRS device was carefully marked with a permanent marker.

The distance between the 3 light sources and the optical detector were 30, 35, and 40 mm. The wavelengths were 760 and 840 nm, which detect the changes in concentrations in the chromophore's hemoglobin (Hb) and myoglobin (Mb), and the 2-wavelength spectrometer that was used allowed the detection of both forms: HbO_2 and HHb.[35] The sum of both signals reflects the concentration of tHb and indicates the volume of blood in the vastus lateralis muscle. As previously reported, alternations in local blood volume reproduce the changes in blood flow if there are no contrasting alternations in erythrocyte velocity.[36] Consequently, oxygen delivery to the muscle can be determined by this NIRS method. The equilibrium between oxygen supply and consumption was calculated using the tissue-saturation index (TSI [%]) as HbO_2 divided by $HbO_2 + HHb \times 100$.

The Cortex Metamax 3B was calibrated for volume before each trial using a precision 3-L syringe (Cortex, Leipzig, Germany) and calibration gas (15.8% O_2, 5% CO_2 in N; Praxair, Germany) to target the range of anticipated fraction gas concentration. Standard algorithms were used for the dynamic account of the time delay between the volume signal and the gas consumption. During all tests the subjects breathed through a turbine flowmeter and a Hans-Rudolph mask. To avoid discomfort and allow the athletes to move freely, all tubing and cables were fixed with straps and tape. Heart rate and velocity were recorded continuously with the gas analyzer to ensure alignment with the spirometric data.

Blood lactate samples were collected in a capillary tube (Eppendorf AG, Hamburg, Germany) and subsequently analyzed in duplicate for the amperometric-enzymatic determination of lactate concentration (Eppendorf AG, Hamburg, Germany). The mean of both samples was employed for the statistical analysis.

Statistical Analyses

All data are reported as mean ± SD, and statistical significance was identified by an alpha value of $P < .05$. Using repeated-measures analysis of variance, both variables were compared at the different time points of the race simulation. If global changes over time were identified, Bonferroni post hoc analysis was employed to detect where the differences occurred. Ratings of perceived exertion were compared with a Student paired *t* test.

Effect sizes from the various outcome measures were calculated using Cohen *d* for the detection of the practical application and meaningfulness of the findings.[37] According to standard practice, small, medium, and large effect sizes were defined as 0.20, 0.50, and 0.80, respectively.[37] The largest effect sizes for the individual parameters are indicated in Table 2. All statistical analyses were carried out using Statistica (version 7.1, StatSoft Inc, Tulsa, OK, USA) software package for Windows.

Results

The time course of TSI and tHb in both vastus lateralis muscles during the 3000-m race simulation, with and without leg compression, is illustrated in Figure 1. The data show that the TSI in both vastus lateralis muscles is

Table 2 All Physiological and Performances Measures Assessed Before, During, and After the 3000-m On-Ice Race Simulation (N = 10), Mean ± SD (Range)

		Type of Clothing		Statistical Analysis	
Variable	**Time point**	**Compression**	**Control**	***P***	***d***
Tissue Saturation Index, %					
Right quadriceps femoris muscle	1st min	78.7 ± 7.5	79.1 ± 7.5	.99	.08
	3rd min	80.1 ± 6.1	79.6 ± 6.5		.12
	last min	79.4 ± 6.2	79.6 ± 6.1		.04
Left quadriceps femoris muscle	1st min	85.3 ± 5.9	86.5 ± 4.8	.99	.31
	3rd min	85.6 ± 5.3	86.3 ± 4.5		.21
	last min	85.4 ± 5.1	86.4 ± 4.6		.31
Total Hemoglobin, µM · cm					
Right quadriceps femoris muscle	1st min	100.0 ± 2.1	98.6 ± 3.2	.33	.76
	3rd min	101.0 ± 3.1	99.3 ± 3.6		.69
	last min	101.4 ± 2.7	99.7 ± 4.5		.64
Left quadriceps femoris muscle	1st min	98.0 ± 2.9	97.5 ± 2.8	.82	.26
	3rd min	99.1 ± 3.4	98.3 ± 3.4		.32
	last min	99.5 ± 3.3	99.0 ± 4.6		.19
Time, s	200 m	22.3 ± 1.5	22.5 ± 1.4	.88	.21
	600 m	61.1 ± 4.5	61.6 ± 3.8		.17
	1000 m	102.3 ± 7.6	102.3 ± 6.3		.01
	1400 m	144.5 ± 10.4	143.8 ± 8.6		.11
	1800 m	188.1 ± 13.5	186.4 ± 11.1		.20
	2200 m	233.3 ± 16.8	23.0 ± 13.7		.30
	2600 m	278.8 ± 20.1	274.4 ± 16.8		.34
	3000 m	324.6 ± 23.3	318.1 ± 19.4		.43
Velocity, m/s	1st min	10.0 ± 0.6	9.9 ± 0.6	.24	.18
	3rd min	9.1 ± 0.4	9.1 ± 0.6		.03
	last min	8.7 ± 0.7	7.9 ± 3.0		.37
Oxygen Uptake, mL/min	1st min	3430 ± 0.89	3430 ± .83	.79	.01
	3rd min	3560 ± 0.92	3630 ± 0.74		.10
	last min	3560 ± 0.87	3620 ± 0.76		.10
Ventilation, L/min	1st min	100 ± 29	90 ± 16	.11	.59
	3rd min	126 ± 30	126 ± 25		.00
	last min	129 ± 28	129 ± 26		.00
Heart Rate, beats/min	1st min	181 ± 6	176 ± 9	.21	.89
	3rd min	187 ± 5	186 ± 6		.11
	last min	188 ± 5	187 ± 5		.16
Blood Lactate Concentration, mmol/L	pre	1.1 ± 0.4	1.2 ± 0.6	.82	.27
	post	14.5 ± 2.2	14.4 ± 1.3		.14
	10′ post	11.5 ± 2.4	11.0 ± 2.1		.28
	30′ post	4.0 ± 1.5	3.4 ± 1.5		.59
Rating of Perceived Exertion, Borg Scale					
Whole body	pre	9.9 ± 1.9	9.6 ± 2.7	.84	.18
	post	17.1 ± 1.2	17.1 ± 1.2		.00
Thigh					
left	pre	9.2 ± 1.9	9.7 ± 2.2	.19	.35
	post	17.8 ± 1.7	16.5 ± 2.0		1.01
right	pre	9.5 ± 2.2	9.9 ± 2.3	.51	.25
	post	17.2 ± 1.7	16.7 ± 2.1		.38
Calf					
left	pre	9.5 ± 3.1	8.4 ± 1.5	.52	.63
	post	13.7 ± 2.6	13.7 ± 3.7		.00
right	pre	9.5 ± 3.1	8.4 ± 1.5	.37	.63
	post	13.7 ± 2.5	14.1 ± 3.7		.18

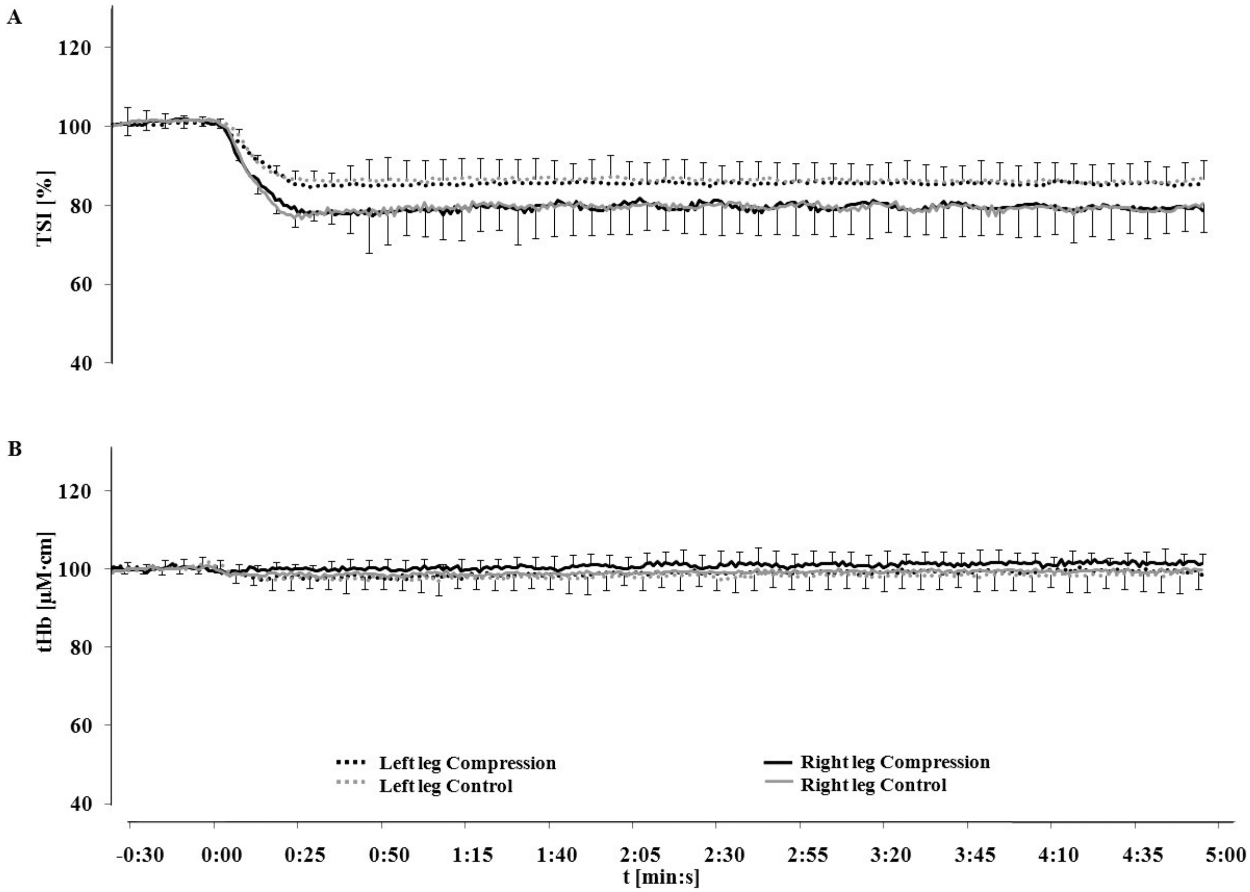

Figure 1 — Temporal changes in (A) tissue-saturation index (TSI) and (B) total hemoglobin (tHb) in both right and left vastus lateralis muscles comparing the 3000-m race simulation with leg-compression clothing and normal racing suit only. Not all standard deviations were illustrated for the sake of clarity since the magnitude was comparable for both legs and types of garments.

asymmetric. The mean TSI of the right quadriceps femoris muscle during the 3000-m race simulation is lower than in the left one ($P < .00$, effect size = 1.81). TSI was unaffected in both the right ($P = .99$, highest effect size = 0.12) and left ($P = .99$, highest effect size = 0.31) vastus lateralis muscle wearing compression under the racing suit applying a pressure of 20.3 ± 2.3 mmHg at the thigh and 24.4 ± 3.1 mmHg at the calf (Table 3). Local blood volume did not differ between the quadriceps femoris muscles ($P = .81$, highest effect size = 0.52) and was unaffected by compression in the right ($P = .33$, effect size = 0.76) and left quadriceps femoris muscles ($P = .82$, highest effect size = 0.51; Figure 1). The statistical analyses revealed no differences between right- and left-leg muscle mass ($P = .93$, effect size = 0.07) or skinfold thickness ($P = .59$, effect size = 0.03).

Lap time ($P = .88$, highest effect size = 0.43) and velocity throughout the 3000-m race simulation remained unchanged ($P = .24$, highest effect size = 0.84) by the application of leg compression in elite speed skaters (Table 2). Oxygen uptake ($P = .79$, highest effect size = 0.10), ventilation ($P = .11$, highest effect size = 0.59), heart rate ($P = .21$, highest effect size = 0.89), blood lactate concentration ($P = .82$, highest effect size = 0.59), and ratings of perceived exertion in any body segment (best $P = .19$, highest effect size = 1.01) were unaffected by wearing compression clothing when compared with the normal racing suit (Figure 2).

Discussion

The current investigation showed an asymmetry in oxygenation of both vastus lateralis muscles during a 3000-m ice speed-skating race simulation that not only occurred during the curves but also remained during the long gliding phases along the straight sections with and without leg compression under the normal racing suit. In addition, this first evaluation of the potential effects of compression on selected cardiorespiratory, circulatory, metabolic, perceptual, and performance parameters during 3000-m ice speed skating revealed no effect whatsoever.

As reported previously, at the onset of short-track speed skating there is an initial decrease in TSI due to

Table 3 Pressure Applied (mmHg) by the Normal Racing Suit and Additional Compression Clothing (N = 10)

	Normal Racing Suit		Racing Suit With Compression	
Subject	Thigh	Calf	Thigh	Calf
1	10.7	11.0	23.7	28.3
2	3.3	5.7	20.0	28.0
3	12.0	12.3	20.9	24.8
4	8.3	9.0	21.0	24.7
5	7.0	11.7	18.7	21.0
6	5.7	9.3	23.7	28.3
7	10.3	12.7	17.7	21.7
8	9.0	12.3	21.3	25.0
9	6.0	8.3	16.7	21.0
10	10.8	14.7	19.1	21.3
Means ± SD (range)	8.3 ± 2.8 (3.3–12.0)	10.7 ± 2.6 (5.7–14.7)	20.3 ± 2.3 (16.7–23.7)	24.4 ± 3.1 (21.0–28.3)

increased oxygen usage in the muscle cells, reaching a steady state for the remaining race after about 25 seconds.[3] Since short-track speed skaters continuously travel anticlockwise, the right leg serves as the "outside leg" to overcome the centrifugal forces of each curve with severe static 1-legged contractions due to the "hang" position.[3] This leads to greater intramuscular pressure, decreasing tissue saturation even more pronouncedly and causing a remarkable oxygenation asymmetry in the right and left vastus lateralis muscles.[3] During cornering, in contrast to the "hang" position in short-track speed skating, which involves prolonged 1-legged contractions, long-track speed skating is characterized by a high step rate.[13] It is interesting that the current investigation demonstrated that the asymmetry in the TSI is also evident during cornering in 3000-m long-track events and even remains unchanged during the long gliding phases along the straight sections of the track.

At the onset of exercise during short-track speed skating the increased demand for oxygen within the muscle cells is counteracted by increased oxygen extraction from HbO_2 and enhanced blood flow that increases oxygen delivery.[3] Since oxygen extraction is expected to remain unaffected due to compression, possible changes in tissue oxygenation should be attributable to altered blood flow. The measurement of tHb with NIRS reflects the changes in local blood volume and, hence, oxygen delivery to the working muscles.[36] The current findings show no effects from leg compression on local blood volume during a 3000-m race simulation in elite speed skating. In contrast, previous studies reported an increased regional blood flow during high-intensity running exercise with the application of leg compression,[18] which was associated with slightly enhanced muscle oxygenation.[19] The altered blood flow in connection with compression has been linked to increased venous return due to an improved muscle pump function.[18,19,32] While running involves intermittent muscle contractions, speed skaters suffer from restricted blood flow due to the high static muscle contractions, especially during cornering.[4] Static muscle contractions of <10% of the maximal voluntary contraction have been shown to maintain blood flow sufficiently to match oxygen demand.[38] The beneficial effects of compression clothing on the muscle pump's function in running exercise might not overcome the high static muscle contractions evident in elite ice speed skating.

The current data showed no effect of leg compression on oxygen uptake, ventilation, and heart rate. While oxygen uptake,[18,20,31] as well as heart rate,[18,39] remained unchanged with leg compression during all-out running and cycling, oxygen uptake was significantly decreased in submaximal running at 12 km/h, indicating an improved running economy.[23] These results were linked to improved circulation due to the textile's support of the muscle pump system and reductions in muscle oscillation. While muscle activity increases in reaction to vibration,[40] metabolic and cardiovascular strain are increased due to the vibration-induced muscle oscillations.[41,42] In supporting the belly of the muscle, compression clothing could reduce muscle oscillation, hence decreasing energy expenditure at a given running velocity.[23] Due to the long gliding phases[4] and, hence, missing high impacts to the lower extremities, muscle oscillations are expected to be much lower in ice speed skating than in running, which would explain the absence of differences in any cardiorespiratory data when comparing conditions with and without leg compression.

It has been proposed that the application of compression clothing shunts the blood from the superficial to the deeper venous system,[15] thus enhancing venous return in supporting the muscle pump system.[14,43] While improved venous return has been suggested to result in an enhanced end-diastolic filling and increased stroke

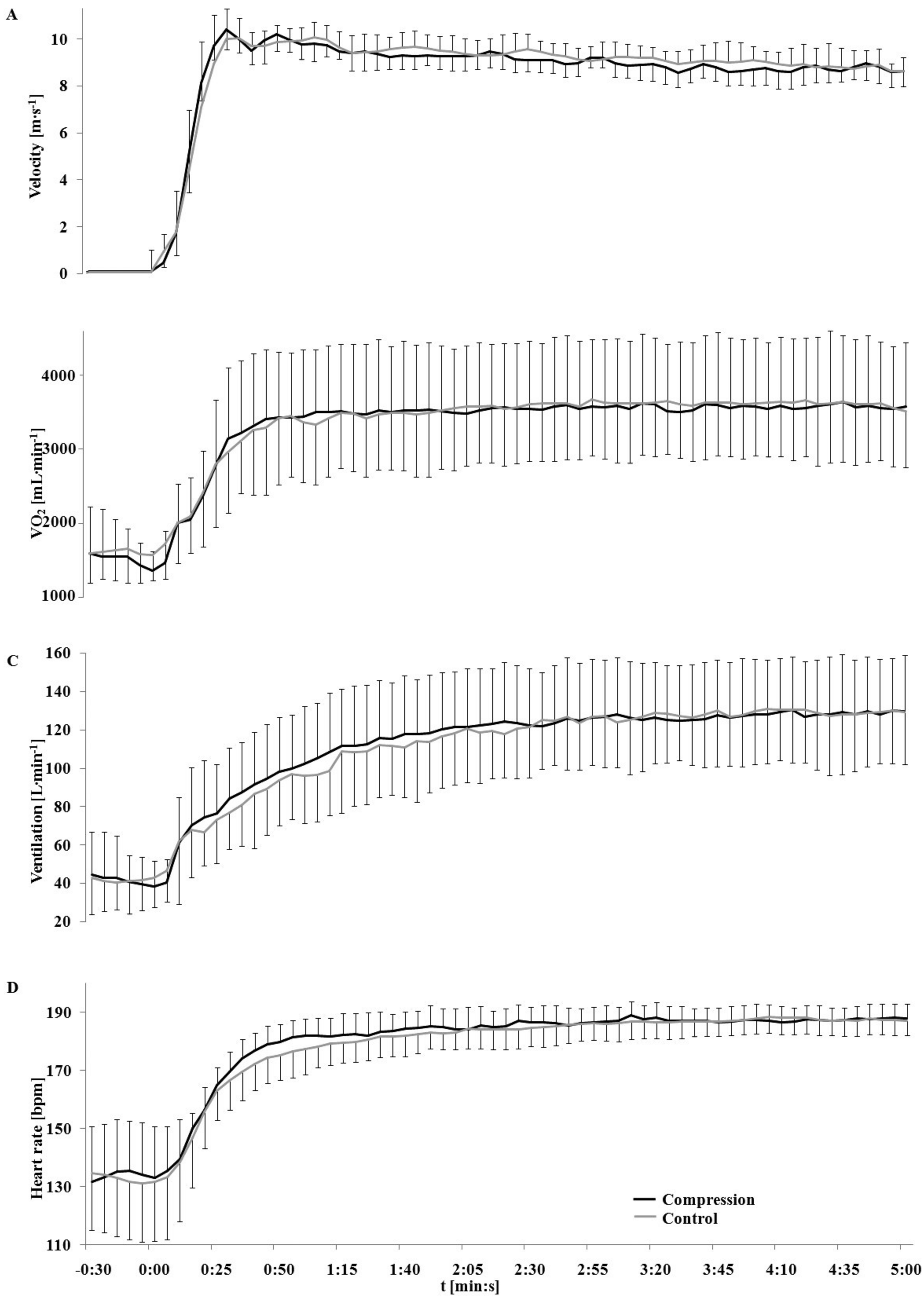

Figure 2 — Comparison of temporal changes in (A) velocity, (B) oxygen uptake, (C) ventilation, and (D) heart rate between the 3000-m race simulations wearing leg compression or the normal racing suit only.

volume,[44] heart rate would be decreased during constant-pace exercise with the application of compression clothing. However, heart rate remained unchanged throughout the whole 3000-m race simulation, indicating no effect of compression clothing on central cardiac parameters. These data support previous findings showing no effect of leg compression on heart rate during high-intensity running exercise.[18,39] Based on the current and previous findings, it remains questionable whether central circulatory blood flow can be affected by the application of leg compression in elite ice speed skaters during high-intensity exercise.

Decreased levels of blood lactate concentration have been previously reported with leg compression during the recovery period after high-intensity exercise.[22] However, the current data revealed, 30 minutes after exercise, higher blood lactate concentrations when compared with those without leg compression, with the following potential explanation: As discussed previously, the application of compression clothing reduces the overall diameter of the vessels, thereby limiting the diffusion capacity and retaining the lactate within the muscle cell and slowing down lactate release into the bloodstream.[22,45]

Ratings of perceived exertion revealed no differences due to the application of leg compression clothing in any body segments. These findings are in line with previous research indicating reduced muscle pain 24 to 48 hours after[24–27] but not during or immediately after high-intensity exercise.[31,44,46–48] Regarding the perceptional response, compression clothing might show more pronounced benefits in reducing muscle pain after rather than during exercise.[28]

Performance during the 3000-m race simulation was unaffected by leg compression. These results are in line with previous findings that showed no performance benefits of leg compression in endurance sports such as high-intensity running[18,31] or cycling.[20] In the current study, variations in sprint time with and without leg compression were within a range of 2%. Earlier research showed that the day-to-day variation of well-trained athletes is mostly related to mean power output throughout the race.[49] Since experienced athletes are relatively independent from motivational influences,[50] as well as not showing large learning effects from one intervention trial to the next,[51] endurance performance is reproducible within a variation of 1% to 2%.[49,52] Therefore, the differences in sprint time may be explained by day-to-day variability, which underlines the finding that compression did not have any effect on 3000-m race performance in elite ice speed skaters.

In this context, pacing has a crucial impact on performance outcomes in endurance sports[53–55] showing a positive pacing strategy during long-distance speed skating World Cup events.[56,57] Because the current findings revealed no differences with and without leg compression in lap time and velocity, these data may indicate that pacing strategy is not affected by the use of compression clothing in 3000-m ice speed skating.

Conclusion and Practical Recommendation

The current investigation in elite speed skating revealed an asymmetry in both vastus lateralis muscles during a 3000-m race simulation. This asymmetry was evident during cornering and remained unchanged during the long gliding phases along the straight sections of the track.

In comparison with a normal racing suit compression clothing had no effect on oxygenation asymmetry or local blood volume in the quadriceps femoris muscles of elite ice speed skaters. In addition, none of the selected cardiorespiratory, circulatory, metabolic, perceptual, and performance parameters were affected. We therefore conclude that there are no performance-enhancing benefits in elite speed skaters wearing leg compression with 20.3 ± 2.3 mmHg at the thigh and 24.4 ± 3.1 mmHg at the calf under the normal racing suit during a 3000-m event.

Future research will need to investigate whether the oxygenation asymmetry is related to adaptation to the nature of the sport and the constant anticlockwise travel in training and competition, rather than to the acute metabolic demands of the exercise.

Further studies should also address the effect of leg compression on shorter race distances and starting performance in elite ice speed skaters due to the possible biomechanical benefits to proprioception and motor control. In addition, leg compression in elite ice speed skating could serve as a recovery tool between repeated sprints or for long-term application up to 48 hours after severe training loads as has been discussed earlier.[28]

Acknowledgments

The authors declare no conflict of interest. We would like to thank all athletes and coaches of for their participation, commitment, and enthusiasm, making this project possible. The study was funded by our own institutional resources.

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Born et al. BMC Sports Science, Medicine, and Rehabilitation 2014, 6:21
http://biomedcentral.com/2052-1847/6/21

BMC Sports Science, Medicine & Rehabilitation

RESEARCH ARTICLE Open Access

A novel compression garment with adhesive silicone stripes improves repeated sprint performance – a multi-experimental approach on the underlying mechanisms

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Abstract

Background: Repeated sprint performance is determined by explosive production of power, as well as rapid recovery between successive sprints, and there is evidence that compression garments and sports taping can improve both of these factors.

Methods: In each of two sub-studies, female athletes performed two sets of 30 30-m sprints (one sprint per minute), one set wearing compression garment with adhesive silicone stripes (CGSS) intended to mimic taping and the other with normal clothing, in randomized order. Sub-study 1 (n = 12) focused on cardio-respiratory, metabolic, hemodynamic and perceptual responses, while neuronal and biomechanical parameters were examined in sub-study 2 (n = 12).

Results: In both sub-studies the CGSS improved repeated sprint performance during the final 10 sprints (best $P < 0.01$, $d = 0.61$). None of the cardio-respiratory or metabolic variables monitored were altered by wearing this garment (best $P = 0.06$, $d = 0.71$). Also during the final 10 sprints, rating of perceived exertion by the upper leg muscles was reduced ($P = 0.01$, $d = 1.1$), step length increased ($P = 0.01$, $d = 0.91$) and activation of the *m. rectus femoris* elevated ($P = 0.01$, $d = 1.24$), while the hip flexion angle was lowered throughout the protocol (best $P < 0.01$, $d = 2.28$) and step frequency (best $P = 0.34$, $d = 0.2$) remained unaltered.

Conclusion: Although the physiological parameters monitored were unchanged, the CGSS appears to improve performance during 30 30-m repeated sprints by reducing perceived exertion and altering running technique.

Keywords: Blood flow, Clothing, Oscillation, Oxygenation, Oxygen uptake, Textile, Tissue saturation index, Venous system, Video analysis

Background

Performance during repeated sprints separated by short periods of rest, a common aspect of team sports [1,2], is determined primarily by neuronal and metabolic factors (e.g., recruitment of muscle fibers and aerobic and anaerobic energy production [3,4]), as well as by the ability to recover between repeated bouts of explosive high-intensity activity [4,5]. Special running gear might improve this performance and, indeed, a recent meta-analysis revealed that lower-body garments that exert compression probably have ergogenic effects during sprinting [6]. Although the mechanism (s) underlying the improvement of repeated sprint performance by compression is not yet clear, the enhanced muscle pump function and venous return [7,8] observed in clinical studies have been proposed as explanation for the elevated local hemodynamics during moderate [9], as well as intermittent high-intensity running [10]. Moreover, reduced blood lactate concentrations following high [11,12] or reduced oxygen uptake during moderate-intensity endurance exercise [13] were also associated with an ergogenic

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effect of compression clothing on local and central hemodynamics.

In a manner similar to compression garments, application of elastic tape, originally used for therapeutic purposes [14], has been found to improve strength and power [15,16], although a recent meta-analysis was inconclusive with respect to muscle activity and pain [17]. Taping is thought to stimulate cutaneous mechano- and nociceptors, thereby altering reflex activation and sensory feedback and increasing electromyographic activity [18,19], thereby enhancing proprioception [20] and muscle strength and power [15,16].

Since compression and taping each influence physiological, biomechanical and perceptual parameters, the primary goal of the present investigation was to examine whether the use of both together improves repeated sprint performance even further. In this context we tested a novel compression garment with adhesive silicone stripes (CGSS) designed to mimic both compression and sports taping. Our secondary goal was to identify the physiological, biomechanical and perceptual effects that might account for the ergogenic properties of this garment.

Methods

To reduce the necessity for bulky laboratory equipment during repeated sprinting, two sub-studies were performed: The first to investigate the influence of CGSS on repeated sprint performance and cardio-respiratory, metabolic, hemodynamic and perceptual variables; and the second to examine whether this special garment might exert an impact on biomechanical properties and running technique.

A total of 24 female subjects were recruited from track-and-field or team sport clubs that regularly use repeated sprinting as part of their training and randomly assigned to participate in sub-study 1 or 2. These women were instructed to report for all testing well-hydrated and to refrain from strenuous exercise for 48 h and from intake of alcohol or caffeine for 24 h beforehand. After being informed of the benefits and risks involved, all provided their written consent to participate. This study was approved by the Ethical Committee of the University of Wuppertal, Germany, and executed in accordance with the Declaration of Helsinki.

Design of sub-study 1

All athletes in sub-study 1 (n = 12; age: 25 ± 3 yrs; height: 167 ± 3 cm; body mass: 61 ± 5 kg; fat mass: 18 ± 5% (mean ± SD)) carried out two sessions of 30 30-m repeated sprints each, one wearing the CGSS and the other with non-compression tights without any adhesive silicone stripes, in randomized order. Each participant wore the same shoes and running shirt during both trials. All sprints were performed on an indoor track at a time when the subjects were not menstruating.

After determination of body mass (Tanita BC 418 MA, Tanita Corp., Tokyo, Japan), the athletes warmed up for 20 min with moderate running, including five 5-m and 10-m sprints. During the repeated sprint protocol, each sprint was initiated by a verbal count-down once each minute. Starting 1 m behind the first gate, they were instructed to complete each 30-m sprint as fast as possible, avoiding pacing, and thereafter to jog back to the starting line at a moderate pace. No feedback concerning performance was provided, in order to promote equal motivation to complete each sprint. Sprint times were recorded by timing gates (TDS Werthner Sport Consulting, Linz, Austria) at the start and end of the 30-m track.

During these trials the women wore a portable telemetric metabolic cart, a chest belt that monitored heart rate, and a portable near-infrared spectroscope (NIRS). Blood samples and ratings of perceived exertion were obtained at the same point in each cycle of sprinting (Figure 1).

Design of sub-study 2

All athletes in sub-study 2 (n = 12; age: 23 ± 2 yrs; height: 169 ± 3 cm; body mass: 61 ± 6 kg; fat mass: 17 ± 4% (mean ± SD)) carried out the same procedure as in sub-study 1, but wore instead a telemetric device to record muscle activation during the repeated sprinting. In this case motion was captured by video-analysis.

The compression garment with adhesive silicone stripes

The CGSS consisted of tights extending from the waist to the ankle with adhesive stripes of silicone on the inner lining designed to compress the anterior and posterior thighs, as well as lower legs, in accordance with previous guidelines [21] (Figure 2). Before the sprints, the levels of compression on the skin by this garment at the *m. gluteus maximus, m. rectus femoris, m. vastus lateralis, m. biceps femoris* and *m. gastrocnemius medialis* were determined three times in accordance with international recommendations employing a pneumatic sensor (SIGaT®, Ganzoni-Sigvaris, St. Gallen, Switzerland) [22], as described previously [23,24].

Data collection

In sub-study 1 gas exchange and heart rate were monitored continuously with a portable breath-by-breath gas analyzer (Metamax 3B, Cortex, Leipzig, Germany) and a chest belt (Polar T31, 1 Hz, Polar Electro Oy, Kempele, Finland), respectively. The gas analyzer used standard algorithms to account for the time delay between inspiration and expiration and to calculate the oxygen consumption. The volume was calibrated using a syringe with a volume of exactly 3 L (Cortex, Leipzig, Germany). The anticipated range of fractional gas concentrations was

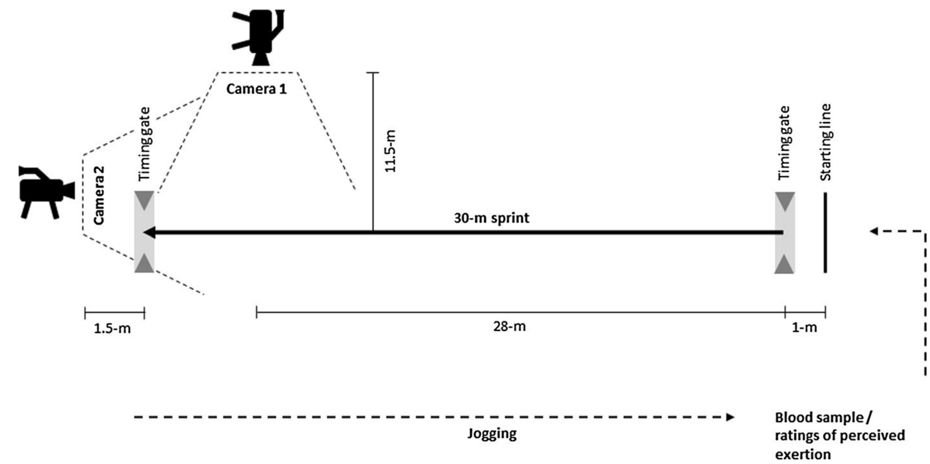

Figure 1 **Schematic illustration of the repeated sprint protocol.**

calibrated before each trial with 15.8% O_2 and 5% CO_2 in N_2 (Praxiar Technology Inc., Danbury, CT, USA). A Hans-Rudolph mask was used to attach the turbine flowmeter and all tubes and cables were fixed in place with tape and straps to assure that the athletes could move freely.

For determination of alternations in muscle oxygenation and blood volume, a wireless NIRS (Portamon, Artinis Medical System, Zetten, The Netherlands) was attached with adhesive tape between the lateral femoral epicondyle and the greater trochanter of the femur across the maximum girth of the belly of the right *vastus lateralis* muscle. None of the participants reported discomfort or disturbance of their normal pattern of movement by any of the devices attached. Since the pattern of oxygenation within the *vastus lateralis* muscle is not uniform, the location of the NIRS during the first trial was indicated with a permanent marker to ensure the same placement during the second set of 30 30-m sprints [25].

The NIRS weighed 85 g and measured 83 × 52 × 20 mm, with distances of 30, 35 and 40 mm between the three light sources and the optical detector. Changes in the oxygenated and deoxygenated levels of hemoglobin (Hb) plus myoglobin (Mb) were monitored at 760 and 890 nm, respectively [26]. In addition, local blood volume was determined on the basis of total hemoglobin (tHb), as indicated by the sum of these signals. The tissue saturation index [%] (TSI %), reflecting the relationship between oxygen delivery and consumption, was calculated as $[[HbO_2]/([HbO_2] + [HHB)] \times 100$.

At the same point in each cycle of sprinting, capillary blood was sampled from the right earlobe for determination of the lactate concentration by amperometric-enzymatic analysis (Ebio Plus, Eppendorf AG, Hamburg,

Figure 2 **Schematic illustration of the CGSS with placement of the silicone stripes on the anterior and posterior leg (a) and detailed structure of the adhesive silicone stripes on the inner lining of the garment (b).**

Germany) and subjective ratings of perceived exertion by the whole body, upper leg muscles (including the gluteal muscles) and lower leg muscles were made on Borg's 6 – 20 scale [27]. Skin temperature on the anterior thigh was determined (MSR Modular Signal Recorder, Prospective Concepts AG, Glattbrugg, Switzerland) both before and after each set of sprints to ensure equal thermoregulatory conditions for both sets.

In sub-study 2 each sprint was recorded with a high-speed camera at a sampling rate of 120 Hz (GoPro, San Mateo, CA, USA) and the kinematic data collected analyzed digitally (Kinovea®, version 0.8.15, Bordeaux, France). This camera was placed 11.5 m away from and at a right angle to a point 28 m along the running track (Figure 1). Markers were attached to the athlete's greater trochanter, medial and lateral femoral epicondyles, as well as to both the medial and lateral forefoot. As previously, markers were fixed to the garment in order not to interfere with its compression properties [28]. To determine step frequency, a second camera was positioned at the end of the running track, 1.5 m to the side of the finish gate to record each step. The number of steps taken during each sprint was counted and divided by the sprint time to obtain step frequency, as described previously [29].

Surface electromyographic activity (EMG) was measured on the right side of the body utilizing pre-gelled bipolar AgCl electrodes (Blue Sensor N, Ambu A/S, Ballerup, Denmark). After shaving, abrading, and disinfecting the skin, these electrodes were attached parallel to the muscle fibers on the skin of the bellies of the *gluteus maximus, rectus femoris, vastus lateralis, biceps femoris,* and *gastrocnemius medialis* muscles. A reference electrode was attached to the tibial bone and all positioning was as recommended by Hermens and Hermie [30]. All signals were transferred to the computer by an analog-to-digital converter card (DAQ 700 A/D card, National Instruments, Austin, TX, USA), differentially amplified and stored in real time by a telemetric recording system (EMG, TeleMyo2400T, Noraxon Inc., Scottdale, AZ, USA). The sampling rate was 1500 Hz. To erase low- and high-frequency noise, all raw signals were passed through a digital band-pass filter (10-500 Hz, 3 dB, Butterworth 2nd edition). The signals were then rectified, smoothed (using the mean values for 50-ms time frames), and normalized to the fastest sprint, as recommended earlier [31]. The integrated EMG (iEMG) was employed as an indicator of muscle activation. All of these analyses were performed with the MyoResearch program (Master Edition version 1.08.27, Noraxon Inc., Scottsdale, AZ, USA).

Statistical analysis

All data are presented as mean values (mean) ± standard deviations (SD). As decided in advance, we were interested in comparing the CGSS and control conditions. After confirming normal distribution, the data from each set of repeated sprints were divided into three equal subsets (sprints 1-10, 11-20, and 21-30), these subsets averaged and data for CGSS and control condition compared using Student's paired *t*-test. A difference with an alpha value of $P \leq 0.05$ was considered to be statistically significant and then adjusted for multiple comparison with the conservative Bonferroni correction, as described previously [32-34]. All of these analyses were performed with the Statistica software package for Windows (version 7.1, StatSoft Inc., Tulsa, OK, USA).

To compare the practical relevance and meaningfulness of the various findings, effect sizes were calculated using the conventional procedure proposed by Cohen [35]. Cohen's d value was calculated by dividing the difference between the means of the intervention and control trials by the average standard deviation for the subject population [35]. In the conventional manner, effect sizes of 0.20, 0.50 and 0.80 were regarded as small, medium and large, respectively [35].

Results

Table 1 documents the pressure applied on the skin by the garment at the various sites on the body during both sub-studies. All physiological, biomechanical and performance values, as well as the level of statistical significance (P) and corresponding effect size (d) for all comparisons made, are presented in Table 2.

Sub-study 1: Cardio-respiratory, metabolic, hemodynamic and perceptional variables during repeated sprinting

Performance of the repeated 30 30-m sprints was improved during the final third of the protocol (sprints 21-30) by wearing the CGSS ($P = 0.02$, $d = 0.37$). Cardio-respiratory and metabolic values (best $P = 0.13$, best $d = 0.54$), the tissue saturation index (best $P = 0.27$, $d = 0.35$), levels of oxy- (best $P = 0.06$, $d = 0.71$), deoxy- (best $P = 0.25$, $d = 0.51$) and total hemoglobin (best $P = 0.4$, $d = 0.44$) as well as skin temperature ($P = 0.75$, $d = 0.18$) were all unaffected by the use of this garment. Furthermore, during the final 10 sprints the CGSS reduced the perceived rating of exertion in the upper

Table 1 The pressure exerted at various sites on the skin by the compression garment with adhesive silicone stripes

Muscle	Pressure [mmHg] (mean ± SD)	
	Sub-study 1 (n = 12)	Sub-study 2 (n = 12)
Gluteus maximus	18.3 ± 4.1	20.2 ± 4.3
Rectus femoris	19.0 ± 4.9	20.2 ± 4.9
Vastus lateralis	17.5 ± 4.4	18.2 ± 4.1
Biceps femoris	19.6 ± 4.7	19.5 ± 5.6
Gastrocnemus medialis	21.7 ± 6.0	19.9 ± 5.6

Table 2 Physiological, biomechanical and performance values (means ± SD) associated with the repeated sprints with and without the compression garment with adhesive silicone stripes (CGSS)

Variable	**Sprints 01-10**				**Sprints 11-20**				**Sprints 21-30**			
	CGSS	**Control**	***P* value**	**ES *d***	**CGSS**	**Control**	**P value**	**ES *d***	**CGSS**	**Control**	**P value**	**ES *d***
Sub-study 1 (n = 12)												
Time [s]	4.97 ± 0.21	5.00 ± 0.22	0.28	0.22	5.09 ± 0.29	5.12 ± 0.29	0.09	0.14	5.12 ± 0.29	5.21 ± 0.34	0.02	0.37
Oxygen uptake [mL·min^{-1}]	2.51 ± 0.53	2.45 ± 0.48	0.47	0.17	2.62 ± 0.63	2.65 ± 0.64	0.77	0.08	2.59 ± 0.6	2.63 ± 0.64	0.71	0.09
Ventilation [L·min^{-1}]	69.1 ± 9.9	68.3 ± 12.6	0.68	0.1	76.5 ± 7.1	78 ± 10.5	0.53	0.23	77.3 ± 8.3	79.1 ± 9.1	0.3	0.31
Heart rate [bpm]	169 ± 7.5	169 ± 7.5	0.92	0.04	178 ± 8.2	177 ± 5.5	0.59	0.2	177 ± 8.5	178 ± 7.2	0.45	0.2
Blood lactate [mmol·L^{-1}]	5.53 ± 1.54	6.17 ± 2.03	0.13	0.5	6.55 ± 1.92	7.29 ± 1.9	0.16	0.54	6.46 ± 2.03	6.84 ± 1.74	0.45	0.29
Tissue saturation index [%]	93.3 ± 3	92.9 ± 3.9	0.68	0.14	91.2 ± 3.4	92.2 ± 4	0.27	0.35	90.7 ± 3.5	91.5 ± 4.6	0.34	0.27
Oxy-hemoglobin [μM·cm]	101 ± 10.8	95 ± 10.4	0.06	0.71	108 ± 14.5	107 ± 17.2	0.8	0.08	109 ± 15.7	110 ± 22.6	0.83	0.07
Deoxy-hemoglobin [μM·cm]	108 ± 6.3	108 ± 7.7	0.87	0.06	113 ± 7.7	116 ± 11.7	0.26	0.42	114 ± 8.7	119 ± 16.9	0.25	0.51
Total hemoglobin [μM·cm]	103 ± 7.2	100 ± 8	0.4	0.44	109 ± 8.7	111 ± 14.4	0.61	0.21	110 ± 9.5	113 ± 20	0.41	0.33
Rating of perceived exertion [Borg's Scale]												
Whole-body	10 ± 2.3	10 ± 2.3	0.98	0.01	14.6 ± 2.2	15.4 ± 1.9	0.09	0.58	17.6 ± 2.3	18.5 ± 1.3	0.13	0.68
Upper leg muscles	9.5 ± 2.7	10.4 ± 2.5	0.29	0.49	13 ± 3.3	14.9 ± 1.7	0.04	1.0	15.7 ± 3.2	17.7 ± 1.9	0.01	1.1
Lower leg muscles	8.6 ± 2.3	8.3 ± 2.3	0.5	0.19	11.4 ± 3.2	11.7 ± 3.2	0.58	0.12	13.6 ± 3.7	14 ± 4	0.64	0.15
Sub-study 2 (n = 12)												
Time [s]	4.87 ± 0.31	4.88 ± 0.39	0.73	0.07	4.88 ± 0.31	4.95 ± 0.40	0.08	0.25	4.85 ± 0.31	4.99 ± 0.36	<0.01	0.61
Hip flexion angle [°]	95.3 ± 4.6	102.8 ± 7.5	<0.01	1.69	96.4 ± 6.3	106.7 ± 6.4	<0.01	2.28	98.4 ± 6.4	106.3 ± 6.1	<0.01	1.78
Step length [m]	2.24 ± 0.1	2.17 ± 0.13	0.03	0.85	2.23 ± 0.13	2.16 ± 0.16	0.07	0.61	2.24 ± 0.14	2.14 ± 0.17	0.01	0.91
Step frequency [Hz]	3.66 ± 0.23	3.65 ± 0.21	0.78	0.08	3.64 ± 0.23	3.65 ± 0.26	0.91	0.03	3.66 ± 0.24	3.63 ± 0.26	0.34	0.2
iEMG [%]												
Gluteus maximus	91.8 ± 11.8	81.7 ± 13.3	0.04	1.14	91.5 ± 28.3	83.5 ± 19.6	0.37	0.46	93.9 ± 31.9	79.2 ± 14	0.13	0.84
Rectus femoris	92.7 ± 12.6	96.7 ± 13.5	0.36	0.44	91.1 ± 11	86.8 ± 15.5	0.5	0.45	95.4 ± 18.5	78.9 ± 19.2	0.01	1.24
Vastus lateralis	88.6 ± 14.7	84.2 ± 6.5	0.31	0.55	89.8 ± 19.9	85.1 ± 13.1	0.53	0.39	95.1 ± 23.9	84.7 ± 10.6	0.23	0.8
Biceps femoris	91.3 ± 21.8	90.3 ± 6.3	0.88	0.08	87.7 ± 19.3	85.8 ± 13.8	0.79	0.16	92.1 ± 24.4	83.8 ± 15.5	0.32	0.58
Gastrocnemius medialis	88.8 ± 18.7	86.5 ± 13.4	0.63	0.21	92 ± 28.7	89.8 ± 15.5	0.79	0.13	96.2 ± 39.5	102.4 ± 24.5	0.65	0.26

Abbreviations. iEMG, integrated EMG; ES, Effect size.

leg muscles ($P = 0.01$, $d = 1.1$), but not in the lower leg muscles ($P = 0.64$, $d = 0.15$) or for the whole body ($P = 0.13$, $d = 0.68$).

Sub-study 2: Biomechanical parameters during repeated sprinting

In sub-study 2, the repeated 30-m sprint times were again significantly improved during the final third of the protocol by wearing the CGSS ($P < 0.01$, $d = 0.61$). Motion capture analysis revealed that this garment significantly reduced the hip flexion angle (best $P < 0.01$, $d = 2.28$). Moreover, during the final 10 sprints the CGSS significantly increased step length ($P = 0.01$, $d = 0.91$), without altering step frequency ($P = 0.34$, $d = 0.2$) and enhanced EMG activity in the *rectus femoris* muscle only ($P = 0.01$, effect size $d = 1.24$).

Discussion

The major findings documented here are that during the final 10 of the 30 repeated sprints wearing the CGSS improved performance, lowered the rating of perceived exertion by the upper leg muscles, increased step length without altering step frequency, and enhanced muscle activation. The hip-flexion angle was reduced by this garment during all of the sprints. None of the cardiorespiratory, metabolic and hemodynamic variables monitored were affected.

Earlier research has demonstrated that performance during short bursts of explosive high-intensity effort is improved by application of compression [28,36,37], in particular (as revealed by the effect size calculation in a recent systematic review) in the case of repeated sprinting and jumping [6]. In contrast, compression was reported not to exert any positive effect on repeated 20-m sprint times during a simulated netball game [38], although the pattern of intensity and rest in this particular study was unfortunately not made clear. Moreover, performance of intermittent 15-m sprints during a simulated field hockey game was unaffected by the application of compression clothing [39], but since there were long active rest periods between these sprints, this protocol may not have induced significant muscular fatigue. In addition, compression clothing did not influence the performance of rugby players during 10 20-m sprints run at the rate of one per minute [40].

To induce extensive muscular fatigue and perceived exertion, 30 30-m sprints were employed here. Application of the CGSS did not affect performance during the early stage of this protocol, only during the final 10 sprints. A recent commentary on repeated sprinting asking for future evaluation of multiple sessions of sprinting also mentioned that pacing becomes more likely as the number of sprints is increased [41]. We cannot excluded the possibility that our participants utilized some pacing strategy.

At the same time, it has been demonstrated that the reproducibility of performance is influenced profoundly by knowing and thereby being able to anticipate the number of sprints [42], as well as by the experience of the athletes involved [43]. For these reasons, we only included subjects whose training involved repeated sprinting. Moreover, all participants knew the number of sprints to be performed beforehand, and received no feedback concerning performance at any time in order to promote equal motivation under both conditions. Therefore, we conclude that the differences in running performance observed were due to the clothing.

In sub-study 1 the CGSS did not significantly alter any of the physiological variables monitored, although the average rating of perceived exertion for the upper leg muscles was reduced during the final 10 of the 30 sprints. For patients with dysfunctional venous valves, compression garments improve local and central hemodynamics [44,45]. Application of pressure to the skin leads to redistribution of blood from the superficial to the deeper venous system, thereby improving muscle pumping and venous return [7,8]. It has been proposed that such enhanced venous return increases the end-diastolic filling and stroke volume of the heart, thereby reducing the heart rate during exercise at any level of intensity [46]. Since our present findings reveal no change in heart rate when wearing CGSS, it is questionable whether such effects observed in patients with dysfunctional venous valves will occur in healthy athletes.

Although compression clothing improves regional blood flow and thereby oxygen availability and utilization in patients suffering from venous insufficiency [47], analogous studies on well-trained endurance athletes are inconclusive. During high-intensity running, compression has been reported to enhance the blood volume, but lower oxygenation of the *vastus lateralis* muscle [9]. In contrast, others have observed no alteration in local blood volume, but elevated tissue oxygenation when wearing compression clothing during intermittent high-intensity running [10]. In addition, positron-emission tomography has recently revealed that blood flow is actually reduced after high-intensity effort wearing compression clothing [24].

The present investigation revealed no change in oxygen uptake with the CGSS, in agreement with previous findings during high-intensity endurance exercise [9,48-50]. During moderate intensity running oxygen uptake was reduced by compression clothing, which is associated with reduced oscillation of the muscle due to the mechanical support provided by the garment [13]. In general, vibration of a muscle increases its activity [51], as well as cardiorespiratory and metabolic demands [52,53]. Since compression clothing attenuates vibration of the muscle belly upon the impact of each step [28], it has been proposed that such clothing also reduces oxygen uptake at a given velocity of running [13]. Indeed, these investigators could detect such a reduction during submaximal (12 km·h^{-1}), but not higher-intensity running. Since the CGSS caused no alternations in the oxygenation index, blood volume or oxygen uptake here, mechanisms other than altered cardio-respiratory and hemodynamic function are likely to explain the improved performance we observed during repeated sprints.

The CGSS significantly lowered our subjects' rating of perceived exertion by the upper leg muscles, which are key contributors to sprint performance [54]. In a similar manner, earlier research has shown that compression clothing lowers perceived exertion, especially in those suffering from severe muscular pain and discomfort [55-58]. However, with our experimental protocol this lower rating of perceived exertion might be a placebo effect. Perceived comfort and exertion exert an important influence on the athlete's performance, irrespective of any physiological and/or biomechanical benefits [37,59]. However, from a practical point of view, "blinding" of our subjects was impossible, since the compression and/or the adhesive silicone stripes are easily perceived. To minimize the placebo effect no detailed information concerning the CGSS or control tights was provided.

As mentioned above, CGSS significantly reduced the hip flexion angle and increased step length, without altering step frequency. Since running velocity is the product of step length times step frequency, any increase in either will improve performance. In general, step length correlates negatively to step frequency [60], but in elite athletes step length appears to exert a larger impact on sprint performance [61]. Moreover, in well-trained, but non-elite athletes (including those involving in track-and-field and team sports), sprint velocity is correlated to step length [60]. Such findings are consistent with our current observation that the CGSS improved performance by increasing step length without changing step frequency.

Mechanoreceptors in the muscle tissue, skin, ligaments and joint capsules provide continuous feedback concerning the movement of these segments [62]. Both compression garment and sports taping have been reported to stimulate these mechanoreceptors, thereby elevating the input to neuromuscular pathways, reflex activation, and sensory feedback [18,19,63-65] and improving proprioception [66,67] and power production [15,16]. Taping alters the electromyographic activity of the *quadriceps femoris* muscle by enhancing the rate of firing and/or recruitment of motor units [15]. However, we detected no significant changes in muscle activation with the CGSS in most of the assessed muscle groups, in line with other findings [68].

Although activation during the final 10 sprints of the protocol was increased significantly with the CGSS in the *rectus femoris* muscle only, large effect sizes concerning better maintenance of muscle activation were evident for other thigh muscles as well. Such a meaningful effect, along with a likely increase in the iEMG, was particularly apparent for the *gluteus maximus* muscles ($P = 0.13$, $d = 0.84$). Power production by the hip extensors exerts a key impact on performance during the late stance phase of sprinting [69-71]. Along with the increased iEMG of the *rectus femoris* muscle, elevation in muscle activation during the late stance phase of each step due to the CGSS might have contributed here to the longer step length and improved performance of repeated sprints.

Acceleration during the initial 10 m of a sprint is characterized by leaning forward and relies primarily on force and power production by the leg extensors [72,73]. In later phases of the sprint with the body upright, running technique, including rapid touchdown, low braking forces, high reverse acceleration of the leg during the stance phase, and rapid forward movement of the leg during the swing phase, determines sprint performance [73-75]. In this later phase, enhanced sensory feedback resulting from the CGSS may have altered proprioception and running technique, explaining the improvement in performance, whereas in earlier studies compression clothing did not enhance performance during repeated sprints over shorter distances (15-m and 20-m) [38-40].

Limitations of the study

All of the trials here were conducted when the subjects were not menstruating. In order to avoid serious interference with their training and competition schedules, they were not required to be in the exact same phase of the menstrual cycle. While early research indicated variations in exercise performance over the course of the menstrual cycle [76], a later review concludes that performance and resistance to fatigue during strength-specific exercise tasks are constant throughout the cycle [77]. A recent report on female athletes performing repeated sprints in three phases of the menstrual cycle found no effect on power production, recovery nor any of the metabolic parameters monitored due to the varying concentrations of estrogen and progesterone [78]. Therefore, we conclude that differences in running performance observed here were not due to hormonal variations.

Conclusions

In both of our current sub-studies the CGSS improved performance in the final 10 of the 30 30-m repeated sprints. While physiological parameters remained unaffected, perceived fatigue was lowered and running technique altered by wearing this garment. Our findings indicate that the improved performance may be due more to altered sprint mechanics than to previously proposed physiological mechanisms, such as alterations in local and/or central hemodynamics or oxygen availability. Future research should be designed to clarify the potential benefits of such a compression garment with adhesive silicone stripes during repeated sprints separated by shorter intervals of rest, where performance relies more heavily on aerobic energy production and rapid recovery.

Competing interests
This investigation was supported financially by the Swedish National Centre of Research in Sports (CIF) as well as by PUMA SE (Herzogenaurach, Germany) and own institutional resources. Neither CIF nor PUMA SE were involved in development of the study design, data collection and analysis, or preparation of the manuscript. There are no other potential conflicts of interest related to this article.

Authors' contributions
Conception and design of the experiments: DPB, FG, BS. Performance of the experiments: DPB, BS. Analyses of the data: DPB, FG, BS. Provision of reagents/materials/analytical tools: DPB, HCH, FG, BS. Preparation of the manuscript: DPB, HCH, FG, BS. All authors read and approved the final manuscript.

Acknowledgements
The authors would like to thank all of the athletes for their enthusiastic participation.

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Received: 22 July 2013 Accepted: 6 May 2014
Published: 30 May 2014

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doi:10.1186/2052-1847-6-21
Cite this article as: Born *et al.*: A novel compression garment with adhesive silicone stripes improves repeated sprint performance – a multi-experimental approach on the underlying mechanisms. *BMC Sports Science, Medicine, and Rehabilitation* 2014 **6**:21.