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Effects of Plyometric Training on Endurance Running Performance in Master Runners: Differences in Training Effects Based on Kinematics
（プライオメトリックトレーニングが中年走者の持久走パフォーマンスに与える影響：運動学に基づくトレーニング効果の差異）

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Doctoral Program in Sport and Health Science
Graduate School of Sport and Health Science
Ritsumeikan University
立命館大学大学院スポーツ健康科学研究科
スポーツ健康科学専攻博士課程後期課程

EIHARA Yuuri
永原　悠利

Supervisor: Professor ISAKA Tadao
研究指導教員：伊坂　忠夫教授

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Chapter 1

Chapter 1. General Introduction

1-1. Preface

Running is one of the world's most popular physical activities that contribute to the primary and secondary prevention of cardiovascular and metabolic diseases, improve mental health, and enhance quality of life [1, 2]. Since the COVID-19 pandemic, interest in outdoor activities has increased, with higher participation among habitual exercisers and many new entrants [3]. Within the recreational population, master endurance runners (typically aged 30–50 years) now account for a rapidly growing segment [4]. This group is characterized by a strong motivation for performance improvement and self-fulfillment, as well as health-related and enjoyment-oriented goals [5]. However, despite their high motivation, achieving further performance enhancement becomes increasingly challenging with age, as physiological limits are approached and recovery capacity gradually declines. Master endurance runners, who represent a physiological transition phase between young and older populations, may exhibit substantial variability in these modifiable factors and their training adaptations. Therefore, exploring effective and practical training strategies for this transitional group is essential to understand how physiological and biomechanical factors interact to determine running performance and to support sustainable performance improvement in the middle-aged population.

Endurance running performance is primarily determined by maximal oxygen uptake ($\dot{V}O_{2max}$) and running economy. In master endurance runners, further increases in $\dot{V}O_{2max}$ are difficult to achieve [6-8]. In contrast, running economy, representing the oxygen or energy cost required to run a given distance, can be relatively more modifiable. Nevertheless, improvements in running economy often plateau even with consistent running training, especially among master endurance runners [7-11], and simply increasing running volume or frequency tends to yield limited benefits [12-14], while elevating injury risk due to

overload [15, 16]. Consequently, several studies have focused on identifying effective and efficient ways to integrate strength-based training into regular running to enhance running economy in this population [16-18].

Resistance training has been widely used as an adjunct to daily running and shown to improve running economy through neuromuscular adaptations and accompanying changes in running kinematics [12-14]. As a well-established and standard training method, high-load resistance training (hereafter referred to as resistance training) has traditionally served as the primary approach for improving running economy. However, it requires specialized equipment and sufficient recovery time, which may limit its practicality for many master runners. In contrast, plyometric training, which can be more easily incorporated into daily running routines because of the lack of constraints related to equipment or training space [12], has been shown to reduce the energy cost of running by enhancing stretch-shortening cycle (SSC) function, including ankle plantarflexor strength [17], jump performance [18, 19], and Achilles tendon stiffness [20, 21]. Nevertheless, the effects of plyometric training on running economy and performance in master endurance runners remain unclear. This gap is critical because age-related declines in neuromuscular function may restrict the degree to which muscle strength and/or SSC-related capacities can improve in middle-aged individuals [22, 23].

Furthermore, substantial inter-individual variability in training responses makes it difficult to determine which type of training is most effective and for whom [24]. A wide range of interrelated factors, including genetic [25, 26], neuromuscular [27, 28], and biomechanical characteristics [24], influences training adaptations. While genetic factors such as muscle fiber composition provide a relatively stable foundation [26, 29], muscle functions (e.g., muscle strength and jump performance) [30] and running kinematics [31] are more adaptable and exert a more substantial and direct influence on running economy and performance [32, 33]. Previous studies have examined how changes in muscle function relate to

improvements in running economy [34, 35]; however, the actual demands placed on these muscle functions are primarily determined by the runner's motion pattern. For example, differences in running kinematics, including foot-strike angle on the sagittal plane and knee extension/flexion range of motion (KE/KF ROM), can alter propulsion strategies, muscle recruitment, and the efficiency of SSC utilization during running [36-41]. However, it remains unclear whether improvements in running economy and performance are driven mainly by increases in muscle function itself or by motion patterns that dictate which muscle functions matter most. Clarifying this would support more individualized, time-efficient training prescriptions and could be an essential consideration for master runners who often have limited training time.

Against this background, this doctoral thesis (1) tests the effects of plyometric training, as an adjunct to daily running, on running economy and performance, with particular attention to its effectiveness and efficiency compared with resistance training, and (2) investigates whether improvements in running economy and performance depend primarily on enhancements in muscle function itself or on motion patterns that alter the relative importance of specific muscle functions. To this end, Chapter 1 summarized previous evidence through a systematic review and meta-analysis to identify effective training variables (e.g., duration, frequency, and intensity) for improving running economy and performance across age groups, and organized literature on how running kinematics shape the muscular demands during running underlying these improvements; Chapter 2 compared the effects and feasibility of resistance versus plyometric training on running economy and 5-km run time to address the first purpose; Chapter 3 applied a kinematics-based clustering approach (foot-strike angle and KE/KF ROM) to test whether associations between lower-limb muscle functions and running economy/performance differ across clusters, addressing the second purpose; Chapter 4 examined the longitudinal mechanisms by which plyometric training influences running economy by modeling interactions among muscle strength, SSC

ability, and running kinematics to reinforce the findings from Chapter 3; and Chapter 5 synthesized these findings to comprehensively answer the two primary aims of this thesis, propose profile-specific guidance, and explored their applicability beyond master endurance runners.

1-2. Terminology

Continuous running training

"Continuous running training" refers to running performed continuously without rest for a distance exceeding 1000 m [42-44].

Endurance (long-distance) running or *running performance*

"Endurance (long-distance) running" refers to running over 3000 m or longer distances. Endurance running performance is mainly assessed by running time to finish 3000 m or longer distances [45]. In this doctoral thesis, the World Athletics (WA) score is considered an indicator of endurance running performance [46]. The term 'running performance' in the doctoral thesis was intended to refer to endurance running performance.

Interval running training

"Interval running training" refers to intermittent running performed in bouts of 1000 m or less, separated by periods of rest or low-intensity activity [42-44].

Master endurance runner

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In this thesis, “master endurance runner” refers to non-elite runners aged 30–50 years. This age group accounts for more than half of the whole participation in worldwide running race events [4].

Muscle function

In this thesis, “muscle function” refers to muscle strength and jump performance, which are associated with running economy and performance [12, 17-19].

Plyometric training

“Plyometric training” was defined as an exercise with body mass and/or ≤ 20% of one repetition maximum (1RM), performing the task as fast as possible, or an exercise with a jump action utilizing the SSC [47].

Reactive jump

“Reactive jump” was termed as an individual’s ability to utilize the SSC, or the ability of the musculotendinous unit to produce a powerful concentric contraction, immediately following a muscle lengthening action [48]. It typically occurs during movements in which body segments are exposed to impact forces (e.g., drop jumps) and is commonly measured using the reactive jump index (flight time divided by ground contact time) [49].

Resistance training

“Resistance training” was defined as an exercise in which the maximal load through the intervention was ≥ 70% 1RM or its equivalent (≤ 12 RM) [45, 50].

Running economy

"Running economy" is defined as the oxygen or energy cost required to run a given distance or at a given submaximal running speed. Submaximal speed is defined as a speed with a respiratory exchange ratio (RER) ≤ 1.00 [51].

Strength training

"Strength training" was often considered the same as resistance training. However, in the present study, strength training is defined more broadly, encompassing both resistance and plyometric training (among others), following the classification adopted in previous studies involving endurance runners [45, 50, 52].

World Athletics (WA) score

"World Athletics (WA) score" reflects the results achieved in a running event based on exact statistical data. Using WA scores can be used to compare results across different running distances [46].

1-3. Abbreviations

Abbreviations listed in this doctoral thesis are those used repeatedly within the main text. Abbreviations that appear only within individual figures or tables are defined locally in their captions and are omitted here.

CMJ: Counter-movement jump

CI: Confidence interval

DF: Dorsiflexion

KE: Knee extension

KF: Knee flexion

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KE/KF: Knee extension and flexion

LMM: Linear mixed-effects model

MDC: Minimal detectable change

PF: Plantarflexion

RER: Respiratory exchange ratio

ROM: Range of motion

RPE: Rate of perceived exertion

SBC: Standardized beta coefficients

SMD: Standardized mean difference

SPM: Statistical parametric mapping

SSC: Stretch-shortening cycle

TE: Typical error

$\dot{V}O_{2max}$: Maximal oxygen uptake

v$\dot{V}O_{2max}$: Velocity of $\dot{V}O_{2max}$

WA score: World Athletics score

1RM: One repetition maximum

1-4. Background and aims

Master endurance runners (30–50 years old) now account for more than half of participation in worldwide running race events [4]. Not only elite runners but also non-elite recreational runners, including master runners, often train with the goal of achieving personal goals [5]. $\dot{V}O_{2max}$ and running economy primarily shape endurance running performance. In master endurance runners, further increases in $\dot{V}O_{2max}$ are

difficult to achieve [6-8], whereas running economy can be modified through muscle functions [53, 54], running kinematics [32, 55], physiological factors [56, 57], and other external factors [58, 59]. Two adjunct modalities are widely used for improving running economy and performance: resistance training, which primarily augments maximal force [60, 61], and plyometric training, which targets SSC efficiency, leg stiffness, and neuromuscular timing [62, 63]. As an adjunct to daily running, however, there is limited information on which training modalities improve running economy and performance, especially in master endurance runners.

Nevertheless, responses to resistance and plyometric training vary considerably among individuals [24], suggesting that the importance of specific muscle functions for running economy and performance differs between runners. Running kinematics may influence which muscle functions are most relevant to running economy and performance. Rearfoot strikers show greater biceps femoris activation than forefoot strikers at the same absolute velocity [39-41], and runners with a larger KE/KF ROM activate the rectus femoris more during propulsion [27]. Conversely, forefoot strikers with smaller KE/KF ROM tend to rely more on SSC utilization of the lower leg musculotendinous complex [38, 40]. Thus, grouping runners with similar kinematic profiles (e.g., foot strike angle and KE/KF ROM) may strengthen the observed relationships between muscle function and running economy/performance.

Therefore, two key issues need to be clarified across age groups of endurance runners, particularly among masters, where evidence remains limited: (1) identifying the effective training modality to improve running economy and performance, and (2) understanding the factors underlying inter-individual variability in responses to adjunct training while focusing on running kinematics. Consequently, (1) Chapter 1 aims to summarize the effectiveness of resistance and plyometric training on running economy

and performance through a systematic review and meta-analysis, providing an overview of the general training effects across endurance runners while also examining the potential influence of age. In addition, the systematic review and meta-analysis explore effective training variables (e.g., intervention period, frequency, training type, and intensity). Furthermore, (2) this chapter aims to organize previous research through a literature review to clarify how differences in running kinematics shape muscular demands during running, thereby underpinning improved running economy and performance.

1-5. Systematic review and meta-analysis

The systematic review and meta-analysis were conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis [64]. The author performed comprehensive searches for articles in the electronic databases of PubMed, Web of Science, and SPORTDiscus with the following search terms and Boolean operators: ("strength training" OR "plyometric training" OR "explosive training" OR "resistance training" OR "weight training" OR "concurrent training" OR "muscle training" OR "isometric training" OR "concentric training" OR "eccentric training" OR "depth jumps" OR "muscular endurance training") AND (running OR marathon OR "distance running" OR "distance runner*" OR "endurance running" OR "endurance runner*" OR "endurance athlete*") AND ("running performance" OR "running economy" OR "time trial" OR "VO2max" OR "oxygen consumption" OR "oxygen uptake" OR "energy cost" OR "blood lactate" OR speed OR "running speed" OR "lactate threshold" OR "run* time") NOT "review." The articles had to be written in English and published up to September 18, 2024 [13, 14, 19, 34, 35, 65-86].

The author independently extracted participant characteristics (performance level, sample size, sex, and age), training protocols, and outcomes for running economy and performance (time-trial

performance) using standardized extraction forms. For each experimental and control group, the number of participants and the pre- and post-intervention means and SD were collected to compute Hedges' *g* and its standard errors (SE). When required numerical data were missing, the author contacted the corresponding authors to obtain additional information wherever possible.

1-5-1. Statistical analyses

A meta-analysis was conducted to estimate the effects of resistance and plyometric training on running economy and performance. For each study, Hedges' *g* with 95% confidence intervals (CIs) was computed from the sample sizes, and pre- and post-intervention means, and SDs for the experimental and control groups were used to quantify the standardized change (i.e., change-score effect size)[87]. Study-level effect sizes were synthesized using a random-effects model and displayed in forest plots. When a study reported multiple training modalities or provided running economy at several speeds (or time-trial results over various distances), within-study effects were combined into a single effect size following Cochrane Handbook guidance [88].

Unless otherwise specified, results are reported as Hedges' *g* [95% CI]. Magnitude was interpreted using conventional thresholds applied to the absolute value of *g*: trivial ≤ 0.20, small 0.20–0.49, moderate 0.50–0.99, and large ≥ 1.00 [89]. CIs that cross zero were interpreted as no definitive change in the outcome [37]. Importantly, improvements in running economy and performance reflect reduced oxygen/energy cost and time to run a given distance, respectively. Thus, Hedges' *g* and the percentage change were expressed as negative values when the variables improved. CIs entirely less than zero indicate a significantly beneficial effect of Hedges' *g*, while CIs entirely greater than zero represent a significantly detrimental effect of Hedges' *g* [90]. In addition, subgroup analyses were performed to determine whether the following variables influenced the improvement in running economy and performance: performance

level (Lv.1 recreational, Lv.2 well-trained, Lv.3 elite levels), age (resistance 21.0–31.5 and 34.1–44.8 years, plyometric 24.3–31.0 and 32.5–33.3 years), intervention period (resistance 6–8 and 10–14 weeks, plyometric 4–6 and 8–10 weeks), training frequency (both for 1–2 and 2 < times/week), resistance training modality (dynamic and isometric), and resistance training load (< 90% of 1RM or > 4RM and ≥ 90% of 1RM or ≤ 4RM). The moderator variables were divided at the median of the studies. All statistical analyses were performed using RStudio (version 2022.02.0 + 443, Boston, MA).

1-5-2. The effects of resistance training on running economy and performance

Overall trend. The study design, training programs, and results of the studies focusing on resistance training were summarized in Table 1-1. Resistance training can increase muscle strength and/or power by altering motor-unit recruitment and firing frequency during voluntary contractions [60, 61]. Greater strength reduces the relative intensity borne by the active muscles during running [91], which, in turn, can improve running economy and performance [18, 91]. In the present meta-analysis, the pooled effect of resistance training showed a significant improvement in running economy (g = -0.32 [95% CI: -0.55, -0.10]) but only a small, non-significant improvement in time-trial performance (g = -0.24 [-1.04, 0.55]; Figure 1-1). The small and imprecise estimate of time-trial performance likely reflects the limited number of studies that have assessed this outcome. For example, Damasceno et al. reported a significant improvement in 10-km performance after resistance training, but the study could not be included because numerical data were not provided [67]. Thus, additional research is needed to clarify this effect.

Table 1-1. Study designs, training variables, and the results of the studies adopting resistance training.

Study designs				Training programs			Results	
Performance level	First author.	Group	Number of participants : sex, age	Period/ frequency (wk/d)	Training mode	Maximal intensity through the intervention	Running economy	Running time trial performance
1	Albracht & Arampitzis [65]	RT	13: M, 27 ± 5	14/3	IRT	90% MVC	10.8 km/h: $\dot{V}O_2$; -5.0%, g = -0.92 [-1.72, -0.12] ECr; -4.7%, g = -0.59 [-1.37, 0.19] 12.6 km/h: $\dot{V}O_2$; -3.4%, g = -0.55 [-1.33 0.23] ECr; -3.5%, g = -0.46 [-1.24 0.32]	–
		Control	13: M, 25 ± 3		–	–	10.8 km/h: $\dot{V}O_2$; 0.0%, g = 0.00 [-0.76, 0.76] ECr; 0.0%, g = 0.00 [-0.76, 0.76] 12.6 km/h: $\dot{V}O_2$; 0.0%, g = 0.00 [-0.76, 0.76] ECr; 0.0%, g = 0.03 [-0.73, 0.79]	–
1	Bohm et al. [66]	RT	13: M = 9, F = 4, 29 ± 5	14/3	IRT	90% MVC	9 km/h: ECr; -3.8%, g = -0.59 [-1.37, 0.19]	–
		Control	10: M = 3, F = 7, 31 ± 3		–	–	9 km/h: ECr; -0.9% g = -0.10 [-1.98, 0.78]	–
1	Damasceno et al. [67, 68]	RT	9: M, 34.1 ± 7.7	8/2	DRT	3RM	12 km/h: $\dot{V}O_2$; -1.4%, g = -0.16 [-1.08, 0.76]	10 km: -2.5% (P = 0.039)
		Control	9: M, 32.9 ± 9.2		–	–	12 km/h: $\dot{V}O_2$; -1.9%, g = -0.17 [-1.09, 0.75]	10 km: -0.7% (NS, $P \geq 0.05$)
1	Ferrauti et al. [69]	RT	11: M = 9, F = 2, 40.0 ± 11.4	8/2	DRT MET	DRT: 3RM MET: 20RM	8.6 km/h: $\dot{V}O_2$; 5.1%, g = 0.60 [-0.26, 1.46] 10.1 km/h: $\dot{V}O_2$; 2.2%, g = 0.30 [-0.54, 1.14]	–
		Control	11: M = 7, F = 4, 40.0 ± 11.4		–	–	8.6 km/h: $\dot{V}O_2$; 4.0%, g = 0.34 [-0.50, 1.18] 10.1 km/h: $\dot{V}O_2$; 4.6%, g = 0.55 [-0.29, 1.39]	–
1	Festa et al. [14]	RT	11: M = 6, F = 5, 44.2 ± 6.0	8/1	DRT	No numerical data	8.5 km/h: $\dot{V}O_2$; -6.3%, g = -0.80 [-1.63, 0.09]	2 km: -4.5%, g = -0.47 [-1.31, 0.37] 10 km: -6.1%, g = -0.71 [-1.57, 0.15]
		Control	9: M = 6, F = 3, 45.4 ± 8.0		–	–	8.5 km/h: $\dot{V}O_2$; 0.8%, g = 0.06 [-0.85, 0.99]	2 km: -2.2%, g = -0.18 [-1.10, 0.74] 10 km: -2.5%, g = -0.14 [-1.06, 0.78]

Table 1-1. Continue.

Study designs				Training programs			Results	
Performance level	First author.	Group	Number of participants : sex, age	Period/ Frequency (wk/d)	Training mode	Maximal intensity through the intervention	Running economy	Running time trial performance
1	Karsten et al. [70]	RT	8: M = 5, F = 3, 39 ± 5.1	6/2	DRT	80% 1RM	–	5 km: -3.5%, g = -0.23 [-1.21, 0.75]
		Control	8: M = 6, F = 2, 30 ± 7.7		–	–	–	5 km: 0.5%, g = 0.03 [-0.95, 1.01]
2	Johnston et al. [72]	RT	6: F, 30.3 ± 1.4	10/3	DRT	6RM	12.8 km/h: $\dot{V}O_2$; -4.1%, g = -0.66 [-1.82, 0.50] 13.8 km/h: $\dot{V}O_2$; -3.8%, g = -0.61 [-1.77, 0.55]	–
		Control	6: F, 30.3 ± 1.4		–	–	12.8 km/h: $\dot{V}O_2$; 0.5%, g = 0.13 [-1.01, 1.27] 13.8 km/h: $\dot{V}O_2$; 0.9%, g = 0.22 [-0.92, 1.36]	–
2	Piacentini et al. [13]	RT	6: M = 4, F = 2, 44.2 ± 3.9	6/2	DRT	90% 1RM	9.75 km/h: $\dot{V}O_2$; -0.5%, g = -0.04 [-1.18, 1.10] 10.75 km/h: $\dot{V}O_2$; -6.2%, g = -0.62 [-1.78, 0.54] 11.75 km/h: $\dot{V}O_2$; 2.8%, g = 0.24 [-0.90, 1.38]	–
		RT	5: M = 3, F = 2, 44.8 ± 4.4			70% 1RM	9.75 km/h: $\dot{V}O_2$; -1.7%, g = -0.25 [-1.50, 1.00] 10.75 km/h: $\dot{V}O_2$; -1.3%, g = -0.19 [-1.42, 1.04] 11.75 km/h: $\dot{V}O_2$; -1.2%, g = -0.12 [-1.35, 1.11]	–
		Control	5: M, 43.2 ± 7.9		–	–	9.75 km/h: $\dot{V}O_2$; 0.0%, g = 0.04 [-1.19, 1.27] 10.75 km/h: $\dot{V}O_2$; -1.3%, g = -0.19 [-1.42, 1.04] 11.75 km/h: $\dot{V}O_2$; -1.2%, g = -0.12 [-1.35, 1.11]	–
2	Vikmoen et al. [74, 75]	RT	11: F, 31.5 ± 8.0	11/2	DRT	4RM	10 km/h: $\dot{V}O_2$; -0.5%, g = -0.10 [-0.98, 0.78]	–
		Control	8: F, 34.9 ± 7.5		–	–	10 km/h: $\dot{V}O_2$; 0.3%, g = 0.05 [-0.93, 1.03]	–

Table 1-1. Continue.

Study designs				Training programs			Results	
Performance level	First author.	Group	Number of participants : sex, age	Period/ Frequency (wk/d)	Training mode	Maximal intensity through the intervention	Running economy	Running time trial performance
3	Fletcher et al. [77]	RT	6: M, 22.2 ± 3.1	8/3	IRT	80% MVC	12.3 km/h: ECr; 1.0%, *g* = 0.12 [-1.02, 1.26] 13.9 km/h: ECr; -0.2%, *g* = -0.03 [-1.17, 1.11] 15.6 km/h: ECr; -0.5%, *g* = -0.10 [-1.24, 1.04]	–
		Control	6: M, 26.3 ± 6.0		–	–	12.3 km/h: ECr; 0.0%, *g* = 0.00 [-1.14, 1.14] 13.9 km/h: ECr; 0.2%, *g* = 0.04 [-1.10, 1.18] 15.6 km/h: ECr; -0.2%, *g* = -0.06 [-1.20, 1.08]	–
3	Millet et al. [78]	RT	7: M, 24.3 ± 5.2	14/2	DRT	90% 1RM	15.0 km/h: $\dot{V}O_2$; -6.9%, *g* = -0.87 [-1.97, 0.23] 17.5 km/h: $\dot{V}O_2$; -5.6%, *g* = -0.85 [-1.95, 0.25]	–
		Control	8: M, 21.4 ± 2.1		–	–	15.0 km/h: $\dot{V}O_2$; 7.1%, *g* = 0.74 [-0.28, 1.76] 17.5 km/h: $\dot{V}O_2$; 5.4%, *g* = 0.49 [-0.51, 1.49]	–
3	Storen et al. [84]	RT	8: M = 4, F = 4, 28.6 ± 10.1	8/3	DRT	4RM	70% of $\dot{V}O_{2max}$: $\dot{V}O_2$; -5.0%, *g* = -0.97 [-2.01, 0.07]	–
		Control	9: M = 5, F = 4, 29.7 ± 7.0		–	–	70% of $\dot{V}O_{2max}$: $\dot{V}O_2$; 1.8%, *g* = 0.23 [-0.75, 1.21]	–

Abbreviations: Lv.1, recreational level; Lv.2, well-trained level; Lv.3, elite level; RT, resistance training; M, male; F, female; IRT, isometric resistance training; DRT, dynamic resistance training; RM, repetition maximum; reps, repetitions; wk, week; d, day; MVC, maximum voluntary contraction; $\dot{V}O_2$, oxygen consumption; ECr, energy cost of running; SD, standard deviation; NS, no significant differences ($P \geq 0.05$) from pre to post.

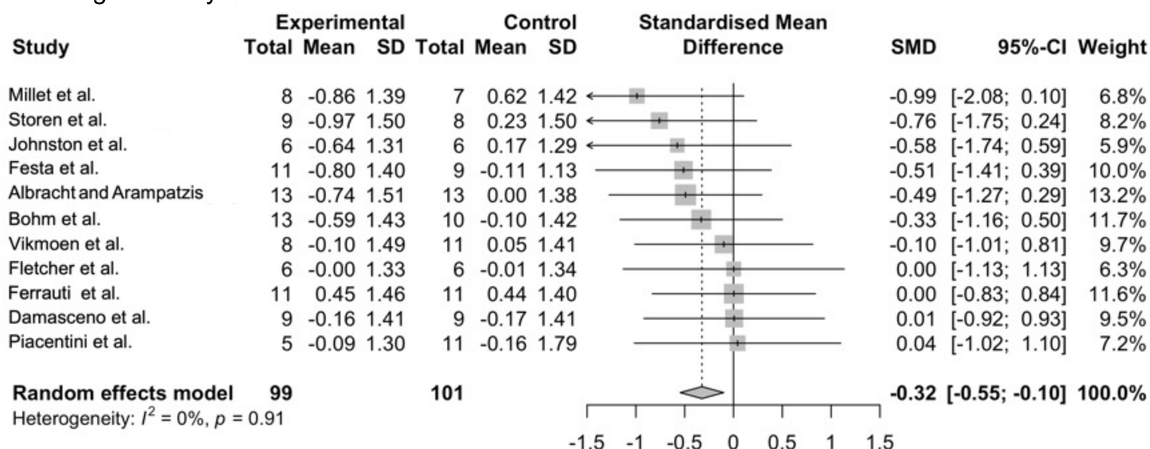
Notation of results

The results for running economy were represented as "running velocity: parameter; percentage changes, Hedges' *g* [95% CIs lower limit, upper limit]."

Regarding running time trial performance, represented as "running distance: percentage changes, Hedges' *g* [95% CIs lower limit, upper limit]."

Data provided in the paper were described when effect sizes could not be calculated due to insufficient data.

This table was modified from the study of Eihara et al. (2022) [12].



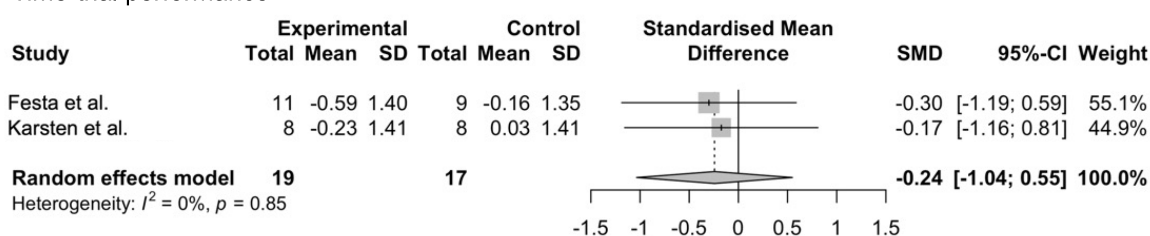


Figure 1-1. Forest plots of effects of resistance training on running economy and time trial performance. Each plot consists of standardized mean difference (SMD) and its 95% CIs. A negative value in SMD represents beneficial effects following resistance training as an adjunct to running training, while a positive value in SMD indicates detrimental effects. The upper panel shows the effects on running economy, and the lower panel shows the effects on time-trial performance. This Figure was modified from the study of Eihara et al. (2022) [12].

Effects of ages and effective training variables. Subgroup analyses were conducted on the effects of resistance training on running economy (Table 1-2), but analyses of running time-trial performance were not performed due to the lack of studies. As a result, resistance training provided significant beneficial effects on running economy for the long training period (*g* = -0.45 [-0.83, -0.08]), young runners (*g* = -0.51 [-0.83, -0.08]), high-performance level (*g* = -0.61 [-1.84, 0.63]), and high training load (*g* = -0.31 [-0.61, -0.02]). Several factors may account for these patterns. First, interventions lasting ≥10 weeks likely provide greater exposure to the training stimulus [92]. Second, whereas younger runners exhibited a moderate, significant improvement, the corresponding effect in master runners (34.1–44.8 years) was trivial (*g* = -0.12 [-0.41, 0.17]); this may partly reflect the ≤ 10-week protocols commonly used in studies of master runners, though age-related factors may also contribute. Third, all elite athletes in the dataset were in the younger category; thus, the apparently larger effects in elites may reflect age rather than competitive level itself. Fourth, near-maximal loading significantly improved running economy, consistent with evidence that such training enhances motor-unit recruitment during maximal voluntary contractions [93, 94] and promotes strength gains with minimal muscle hypertrophy, thereby reducing the relative intensity during running. Finally, training frequency did not significantly impact the effects of resistance training on running economy (low-frequency: *g* = -0.28 [-0.51, 0.02]; high-frequency: *g* = -0.36 [-1.02, 0.35]). Several previous studies have also indicated that not the training frequency but the training volume (period) would be more effective for improving muscle function [95, 96].

Focusing specifically on the relatively older runners (34.1–44.8 years) within the present cohort, the pooled effect of resistance training on running economy was trivial and non-significant (*g* = -0.12 [-0.41, 0.17]). Beyond shorter intervention periods, older adults often display attenuated hypertrophic responses compared with younger adults, potentially limiting gains in oxidative capacity and strength [97, 98]. Nevertheless, Piacentini et al. reported a 6.2% improvement in running economy after 6 weeks of

heavy resistance training (85–90% 1RM) in well-trained master runners [13]. Moreover, prior work indicates that neural adaptations to strength training are similar to those in younger adults, irrespective of sex [99, 100]. Collectively, these findings suggest that running economy in master endurance runners can be improved either by extending the intervention period or by employing high-load protocols that emphasize neural adaptations, over more extended time frames (but not frequency).

Table 1-2. Subgroup analyses regarding effects of resistance training on running economy.

Moderator variables	Hedges' *g* [95% CIs LL, UL]	Interpretation
Performance level		
Recreational level	-0.27 [-0.59, 0.04]	Small
Well-trained level	-0.18 [-0.92, 0.56]	Trivial
Elite level	-0.61 [-1.84, 0.63]	Moderate
Age		
Young (21.0–31.5 years)	-0.51 [-0.83, -0.19]	Moderate
Old (34.1–44.8 years)	-0.12 [-0.41, 0.17]	Trivial
Intervention period		
Short (6–8 weeks)	-0.21 [-0.56, 0.15]	Small
Long (10–14 weeks)	-0.45 [-0.83, -0.08]	Small
Training frequency		
Low (1–2 days/week)	-0.28 [-0.51, 0.02]	Small
High (2 < days/week)	-0.36 [-1.02, 0.35]	Small
Training modality		
Dynamic training	-0.32 [-0.64, 0.00]	Small
Isometric training	-0.33 [-0.89, 0.22]	Small
Training load		
< 90% 1RM or > 4RM	-0.17 [-1.05, 0.70]	Trivial
≥ 90% 1RM or ≤ 4 RM	-0.31 [-0.61, -0.02]	Small

Data are standardized mean differences for effect size values (Hedges' *g*).

Hedges' *g* represents time (pre vs. post) by group (experimental vs. control) interaction.

Abbreviations: RM, repetition maximum; CIs, confidence intervals; LL, lower limit; UL, upper limit.

This table was modified from the study of Eihara et al. (2022) [12].

1-5-3. The effects of plyometric training on running economy and performance

Overall trend. The study design, training programs, and results of the studies focusing on plyometric training were summarized in Table 1-3. Plyometric training, which primarily involves various jumping actions utilizing the SSC ability [62], can enhance elastic energy storage and reutilization, thereby reducing the energetic cost of running [62, 63]. However, the pooled effect size for plyometric training was trivial for running economy (g = -0.13 [-0.47, 0.21]) and small for running time-trial performance (g = -0.17 [-0.27, -0.06]; Figure 1-2). One possible reason for the minor effects of plyometric training on running economy is the differences in training period between resistance and plyometric training. The average and 95% CIs of the training period in resistance training were 9.6 [95% CIs: 8.0, 11.2] weeks, while those of plyometric training were 6.9 [95% CIs: 5.8, 8.0] weeks. The intervention period influenced running economy outcomes, and prior work suggests that ≥ 10 weeks of plyometric training maximizes the probability of meaningful gains in jumping performance [101], which, in turn, could enhance running economy and performance [102, 103]. Nevertheless, 6 of 8 studies have used plyometric training for 6 weeks or less [19, 35, 79, 80, 83], which may not have been sufficient to improve running economy substantially. While there is room for future consideration [23], the available evidence indicates that plyometric programs of ≥ 10 weeks are likely necessary to improve running economy.

Table 1-3. Study designs, training variables, and the results of the studies adopting plyometric training.

Study designs				Training programs		Results	
Performance level	First author.	Group	Number of participants : sex, age	Period/ frequency (wk/d)	Training	Running economy	Running time trial performance
1	García-Pinillos et al. [34]	PT	51: M = 27, F = 24, 27.2 ± 8.6	10/2-4	Jump rope 5 min per session 10-20 min/wk	–	3 km: -3.0%, g = -0.72 [-0.72, 0.10]
		Control	45: M = 24, F = 21, 26.1 ± 6.3		–	–	3 km: -1.5%, g = -0.13 [-0.56, 0.30]
1	Machado et al. [85]	PT	8: M 39.0 ± 4.0	8/2	45 cm drop jump only. 6 sets × 30 s with 30 s of recovery.	–	10 km: -11.6%, g = -0.89 [-1.91, 0.13]
		Control	8: M 39.0 ± 4.0		–	–	10 km: -0.3%, g = -0.03 [-1.01, 0.95]
1	Pellegrino et al. [79]	PT	11: M = 7, F = 4, 32.5 ± 2.0	6/2-3	Squat jump, etc. 2-3 sets × 6-15 reps total contacts: 60-228 per session adapted from Spurrs et al. [83]	7.7 km/h: ECr; -0.5%, g = -0.16 [-1.00, 0.68] 9.2 km/h: ECr; -1.0%, g = -0.38 [-1.22, 0.46] 10.6 km/h: ECr; -1.3%, g = -0.40 [-1.24, 0.44] 12.1 km/h: ECr; -0.8%, g = -0.24 [-1.08, 0.60] 13.5 km/h: ECr; 2.3%, g = 0.65 [-0.21, 1.51] 15.0 km/h: ECr; -0.3%, g = -0.07 [-0.91, 0.77] 16.4 km/h: ECr; 5.8%, g = 1.07 [0.17, 1.97]	3 km: -2.6%, g = -0.66 [-1.51, 0.21]
		Control	11: M = 7, F = 4, 34.2 ± 2.6		–	7.7 km/h: ECr; 1.8%, g = 0.62 [-0.24, 1.48] 9.2 km/h: ECr; 2.3%, g = 0.93 [0.05, 1.81] 10.6 km/h: ECr; 2.9%, g = 1.01 [0.13, 1.89] 12.1 km/h: ECr; -0.7%, g = -0.22 [-1.06, 0.62] 13.5 km/h: ECr; -2.8%, g = -0.79 [-1.65, 0.07] 15.0 km/h: ECr; -3.1%, g = -0.81 [-1.67, 0.05] 16.4 km/h: ECr; -4.4%, g = -0.46 [-1.30, 0.38]	3 km: -1.6%, g = -0.34 [-1.18, 0.50]

Table 1-3. Continue.

Study designs				Training programs		Results	
Performance level	First author.	Group	Number of participants : sex, age	Period/ frequency (wk/d)	Training	Running economy	Running time trial performance
2	Ache-Dias et al. [80]	PT	9: :M = 4, F = 5, 24.3 ± 3.1	4/2	Continuous jump only 4-6 sets × 30 s with 5 min of recovery	9 km/h: $\dot{V}O_2$; -2.1%, *g* = -0.14 [-1.06, 0.78] ECr; -2.1%, *g* = -0.14 [-1.06, 0.78]	–
		Control	9: :M = 4, F = 5, 31.3 ± 5.7		–	9 km/h: $\dot{V}O_2$; -1.3%, *g* = -0.07 [-0.99, 0.85] ECr; -2.5%, *g* = -0.14 [-1.06, 0.78]	–
2	Berryman et al. [81]	PT	11: M, 31 ± 7	8/1	Drop jump (20, 40 or 60 cm) 3-6 sets × 8 reps	12 km/h: $\dot{V}O_2$; -6.9%, *g* = -0.99 [-1.87, -0.11] $\dot{V}O_2$ (kg$^{0.75}$); -7.0%, *g* = -0.94 [-1.82, 0.06]	3 km: -4.8%, *g* = -0.44 [-1.28, 0.40]
		Control	5: M, 29 ± 11		–	12 km/h: $\dot{V}O_2$; 0.0%, *g* = 0.00 [-1.23, 1.23] $\dot{V}O_2$ (kg$^{0.75}$); 0.0%, *g* = 0.00 [-1.23, 1.23]	3 km: -3.0%, *g* = -0.18 [-1.41, 1.05]
2	Do Carmo et al. [86]	PT	15:M, 33.3 ± 6.1	9/2	Squat jump, etc. 3-5 sets × 6 reps, adapted from Spurrs et al. [83]	average $\dot{V}O_2$ of 10 km/h, 12 km/h: -0.9%, *g* = -0.15 [-0.89, 0.59]	10 km: -1.0%, *g* = -0.16 [-0.89, 0.57]
		Control	13:M, 33.3 ± 6.1		–	average $\dot{V}O_2$ of 10 km/h, 12 km/h: 0.0%, *g* = 0.00 [-0.76, 0.76]	10 km: 0.1%, *g* = 0.06 [-0.70, 0.82]
2	Spurrs et al. [35]	PT	8: M, 25 ± 4	6/2-3	Squat jump, etc. 2-3 sets × 6-15 reps	12 km/h: $\dot{V}O_2$; -6.7%, *g* = -0.42 [-1.42, 0.58] 14 km/h: $\dot{V}O_2$; -6.4%, *g* = -0.42 [-1.42, 0.58] 16 km/h: $\dot{V}O_2$; -4.2%, *g* = -0.28 [-1.26, 0.70]	3 km: -1.6%, *g* = -0.13 [-1.11, 0.85]
		Control	9: M, 25 ± 4		–	12 km/h: $\dot{V}O_2$; 0.5%, *g* = 0.04 [-0.88, 0.96] 14 km/h: $\dot{V}O_2$; 0.5%, *g* = 0.04 [-0.88, 0.96] 16 km/h: $\dot{V}O_2$; 0.5%, *g* = 0.04 [-0.88, 0.96]	3 km: -0.5%, *g* = -0.09 [-1.01, 0.80]

Table 1-3. Continue.

Study designs				Training programs		Results	
Performance level	First author.	Group	Number of participants : sex, age	Period/ frequency (wk/d)	Training	Running economy	Running time trial performance
2	Turner et al. [19]	PT	10: M = 4, F = 6, 34 ± 12	6/3	Vertical jump, etc. 5-20 reps per session	9.7 km/h: $\dot{V}O_2$; NS 11.3 km/h: $\dot{V}O_2$; improve, $P < 0.05$	–
		Control	8: M = 4, F = 4, 27 ± 5		–	9.7 km/h: $\dot{V}O_2$; NS 11.3 km/h: $\dot{V}O_2$; NS	–
3	Ramirez-Campillo et al. [83]	PT	17: M = 9, F = 8, 22.1 ± 2.7	6/2	Drop jump only 2 sets × 10 jumps (20, 40, 60 cm box)	–	2.4 km: -4.0%, g = -0.39 [-1.08, 0.30]
		Control	15: M = 10, F = 5, 22.1 ± 2.7		–		2.4 km: -1.3%, g = -0.11 [-0.84, 0.62]

Abbreviations: Lv.1, recreational level; Lv.2, well-trained level; Lv.3, elite level; PT, plyometric training; M, male; F, female; reps, repetitions; wk, week; d, day; $\dot{V}O_2$, oxygen consumption; ECr, energy cost of running; vLT, velocity of lactate threshold; $\dot{V}O_2$ ($kg^{0.75}$), allometric scaling ($mL/min/kg^{-0.75}$); NS, no significant differences ($P \geq 0.05$) from pre to post.

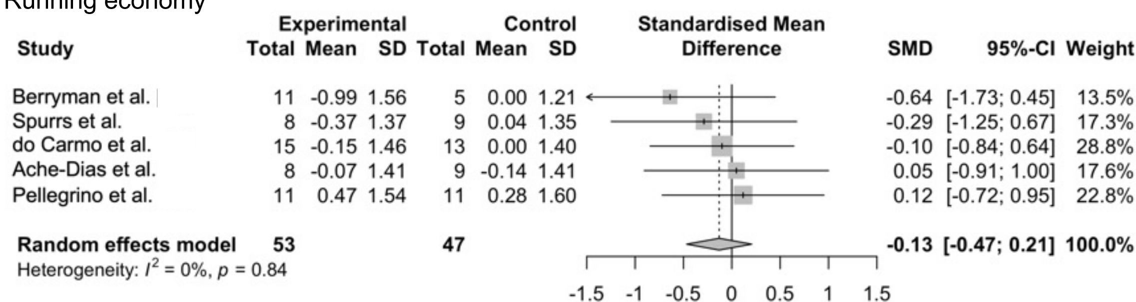
Notation of results

The results for running economy were represented as "running velocity: parameter; percentage changes, Hedges' g [95% CIs lower limit, upper limit]." Regarding running time trial performance, represented as "running distance, percentage changes, Hedges' g [95% CIs lower limit, upper limit]."

Data provided in the paper were described when effect sizes could not be calculated due to insufficient data.

This table was modified from the study of Eihara et al. (2022) [12].

Running economy



Time-trial performance

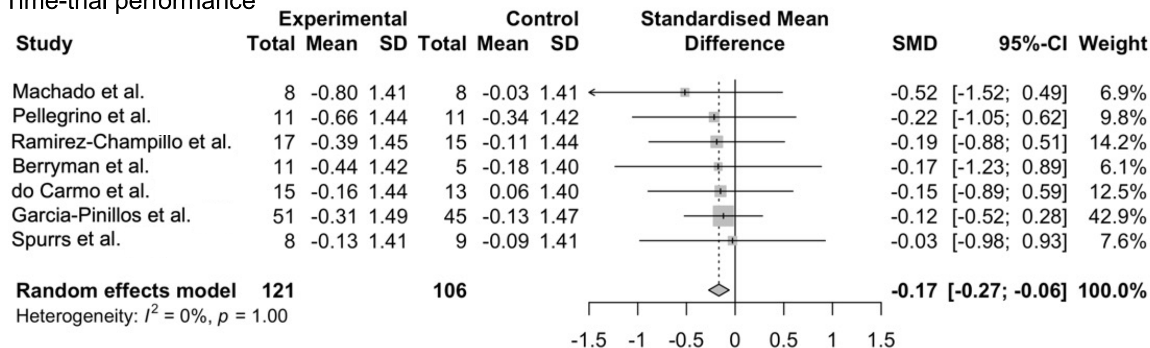


Figure 1-2. Forest plots of effects of plyometric training on running economy and time trial performance. Each plot consists of SMD and its 95% CIs. A negative value in SMD represents beneficial effects following plyometric training as an adjunct to running training, while a positive value in SMD indicates detrimental effects. The upper panel shows the effects on running economy, and the lower panel shows the effects on time-trial performance.

This figure was modified from the study of Eihara et al. (2022) [12].

Effects of ages and effective training variables. Subgroup analyses suggested more favorable effects of plyometric training on running economy in well-trained runners (*g* = -0.20 [-0.62, 0.22]), younger runners (*g* = -0.26 [-1.09, 0.58]), and with a more extended training intervention period (*g* = -0.26 [-0.67, 0.15]; Table 1-4). These results mirrored the patterns observed for resistance training. Regarding performance level, prior work has shown that individuals with weaker lower-limb muscle strength exhibit longer ground contact times during drop jumps [104]. As running speed increases from 7.2 km/h to 18.7 km/h, contact times during the stance phase reduced from 343 ms to 188 ms [105, 106]. Improvements in short-contact-time jump performance induced by plyometric training have been linked to better running economy at faster velocities [107]. These observations suggest that recreational runners, who likely have lower force-generation capacity, may perform plyometric tasks with longer contact times; accordingly, programs emphasizing short-contact-time, fast SSC actions could be more conducive to economy gains in this group. On the other hand, low-training frequency was slightly more effective for improving running economy (*g* = -0.19 [-0.53, 0.15]) than high-training frequency (*g* = -0.10 [-1.61, 1.49]), suggesting that even low-frequency plyometric training could improve running economy.

For relatively older runners within the present cohort (32.5–33.3 years), evidence on the effects of plyometric training remains very limited. Older adults generally achieve lower jump heights, have difficulty maintaining short ground contact times during jumps, and exhibit reduced lower-limb strength relative to younger adults, which may constrain SSC-specific adaptations [108]. Consistent with our subgroup findings, master runners may derive smaller benefits in running economy and performance from typical short-duration plyometric protocols; however, data are sparse, and further trials are needed to clarify efficacy in this population. In both resistance and plyometric training, training frequency appears to have a relatively minor influence on improvements in running economy, whereas extending the overall intervention duration (i.e., 10 weeks) is likely more critical for eliciting meaningful adaptations.

Table 1-4. Subgroup analyses regarding effects of plyometric training on running economy.

Moderator variables	Hedges' *g* [95% CIs LL, UL]	Interpretation
Performance level		
Recreational level	0.12 [-0.72, 0.95]	Trivial
Well-trained level	-0.20 [-0.62, 0.22]	Small
Elite level	–	
Age		
Young (24.3–31.0 years)	-0.26 [-1.09, 0.58]	Small
Old (32.5–33.3 years)	-0.01 [-1.38, 1.37]	Trivial
Intervention period		
Short (4–6 weeks)	-0.06 [-0.67, 0.55]	Trivial
Long (8–10 weeks)	-0.26 [-0.67, 0.15]	Small
Training frequency		
Low (1–2 days/week)	-0.19 [-0.53, 0.15]	Small
High (2 < days/week)	-0.10 [-1.61, 1.49]	Trivial

Data are standardized mean differences for effect size values (Hedges' *g*).

Hedges' *g* represents time (pre vs. post) by group (experimental vs. control) interaction.

Abbreviations: CIs, confidence intervals; LL, lower limit; UL, upper limit.

This table was modified from the study of Eihara et al. (2022) [12].

1-5-4. The main findings and knowledge gaps

The main findings were that:

1. Resistance training, as an adjunct to daily running, can improve running economy (and possibly performance) more than plyometric training in mixed-aged endurance runners.
2. The effects of resistance training on running economy were trivial in master endurance runners, but few studies have examined the effects of plyometric training on running economy and performance in the corresponding age group.
3. Running economy can be improved with longer interventions (regardless of training frequency) or via neuromuscular adaptations elicited by high-load resistance training, and plyometric training that prioritizes short ground-contact (fast SSC) actions may support improvements in running economy among master runners.

However, the comparative effectiveness of resistance versus plyometric training cannot be determined from the present evidence because intervention periods differed substantially across studies. Consequently, the superiority of one modality over the other for improving running economy and performance cannot be inferred. Nevertheless, the present review allowed us to estimate the magnitude of training-induced improvements in running economy and performance, and to identify several training variables that appear to be effective.

1-6. Literature review

The former section showed a substantial variability in the training effects of resistance and plyometric training on running economy and performance, in a mixed-aged group (*g* = -0.99 to 0.12). To address this heterogeneity, this section clarifies how differences in running kinematics specify the muscle functions most relevant to running economy and performance. Specifically, this section synthesizes how the relationships between muscle functions and running economy/performance are mediated by running kinematics (e.g., foot-strike pattern and KE/KF ROM). To achieve this aim, this section focuses on evidence showing how running kinematic characteristics alter muscle activation, particularly how rearfoot vs. forefoot striking and a large vs. small KE/KF ROM shift the contributions of the hamstrings, quadriceps, and the reliance on the SSC (the interaction of plantarflexors and the Achilles tendon).

1-6-1. Effects of foot-strike pattern on the muscle activation pattern during running

Foot-strike angle on the sagittal plane organizes the distribution of joint work and the timing of neuromuscular activity across the lower limb. A more plantarflexed (forefoot) strike is consistently accompanied by earlier and larger pre-activation of the triceps surae, a steeper rise in ankle moment shortly after foot-strike, and comparatively reduced early quadriceps demand at the knee joint [40]. Previous studies showed robust soleus-dominant activation before and during early stance, with ankle power peaking in mid-stance and short ground contact times requiring rapid force transmission [40, 109, 110]. Furthermore, modeling research indicated that soleus fascicles operate near quasi-isometric lengths while the Achilles tendon bears much of the elastic strain in more plantarflexed

runners [111, 112]. This implies that forefoot runners need high reactive strength, pre-activation of the plantarflexors, and sufficient tendon stiffness to tolerate ground-contact forces (Figure 1-3).

By contrast, a dorsiflexed (rearfoot) strike elicits a pronounced tibialis anterior activation at touchdown and greater eccentric activity of the hamstrings (knee flexors) to manage collision [40]. Subsequent propulsion also relies on the increases in hamstrings and hip extensor activity through mid- to late-stance [41, 110, 113, 114]. These features imply that a different level of reliable hamstring strength is required to transition from braking to propulsion while maintaining knee stability. Taken together, foot-strike angle shifts the neuromuscular emphasis. Namely, forefoot strike patterns prioritize SSC ability for efficient propulsion, whereas rearfoot strike patterns prioritize KF strength during the late-stance propulsion (Figure 1-3).

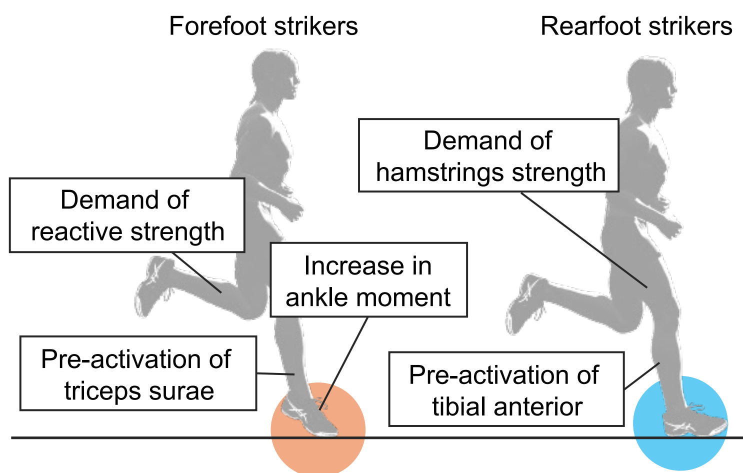


Figure 1-3. Summarization of the characteristics of forefoot strikers and rearfoot strikers.

1-6-2. Effects of KE/KF ROM on the muscle activation pattern during running

KE/KF ROM during the stance phase also modulates both the timing and the pattern of lower-limb muscle activation. When KE/KF ROM is small, pre-activation of lower-limb muscles before touchdown would be more pronounced, and agonist-antagonist co-contraction around the knee joint increases [115-117]. Moreover, because the ankle moment rises rapidly, the triceps surae deliver an ankle-centered force impulse, while the Achilles tendon stores and releases elastic energy [111, 112]. Around the knee joint, stability is maintained mainly by simultaneous activity of the quadriceps and hamstrings [110, 118]. Practically, this pattern demands fast reactive strength of the plantarflexors, a high rate of force development, and effective utilization of the SSC without unnecessary braking [118, 119] (Figure 1-4).

When KE/KF ROM is larger, runners prepare less before foot strike and spend longer on the ground [120]. Activation progresses more in sequence across joints rather than co-activation [40]. At touchdown, the quadriceps (knee extensors) work eccentrically to absorb the ground contact forces, and early in stance, the quadriceps and hamstrings ramp up to shift from braking to push-off [110, 118]. Because co-contraction is reduced in this pattern, joint motions and muscle activation are more decoupled [40]. Consequently, propulsion relies less on an ankle-spring rebound and more on coordinated timing among segments [117, 118]. Accordingly, the capacity demands shift toward eccentric KE function, adequate activation of the quadriceps and hamstrings due to a larger KF excursion, and robust hip and knee stabilization [117, 118]. An observational study suggested that small KE/KF ROM show greater co-contraction and tighter ankle-knee phase locking. In contrast,

more compliant styles show greater joint-specific activation and higher KE activation (Figure 1-4) [40].

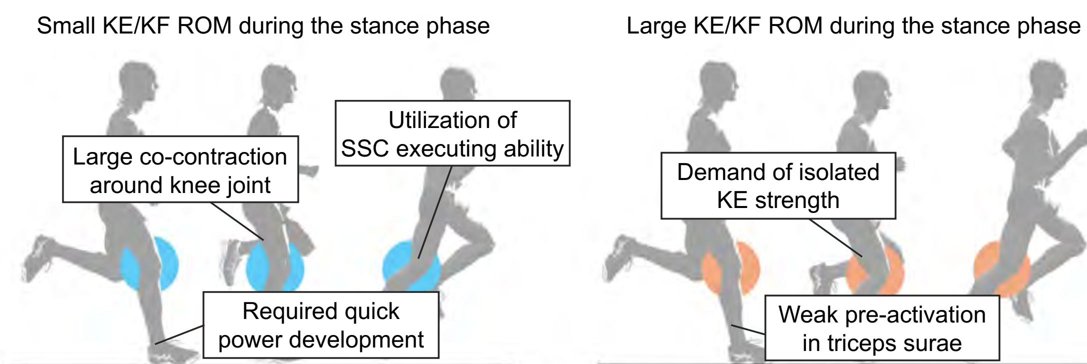


Figure 1-4. Summarization of the characteristics of runners with small and large KE/KF ROM. **Abbreviations**: KE, knee extension; KF, knee flexion; ROM; range of motion; SSC, stretch-shortening cycle.

1-6-3. Mapping running style to required muscle functions

In forefoot runners with small KE/KF ROM, propulsion is ankle-centered with short ground contact, and the demand on SSC increases. This indicates that it would be needed strong plantarflexor pre-activation, high rate of force development, and sufficient Achilles tendon stiffness for elastic energy transfer [111, 112, 118]. By contrast, rearfoot runners shift work proximally, contribute less via the SSC, and depend more on KF strength to absorb impact and transition from braking to propulsion [110, 117, 118]. In runners with large KE/KF ROM, the mechanical emphasis on KE strength is more influential in managing KF excursion during running. Accordingly, relationships between muscle functions and both economy and performance become clearer when analyses are restricted to

cohorts with shared kinematics (foot-strike pattern and KE/KF ROM). For example, KF strength should be a key determinant in dorsiflexed rearfoot runners, whereas KE strength should weigh more heavily in groups characterized by large KE/KF ROM (Figure 1-5).

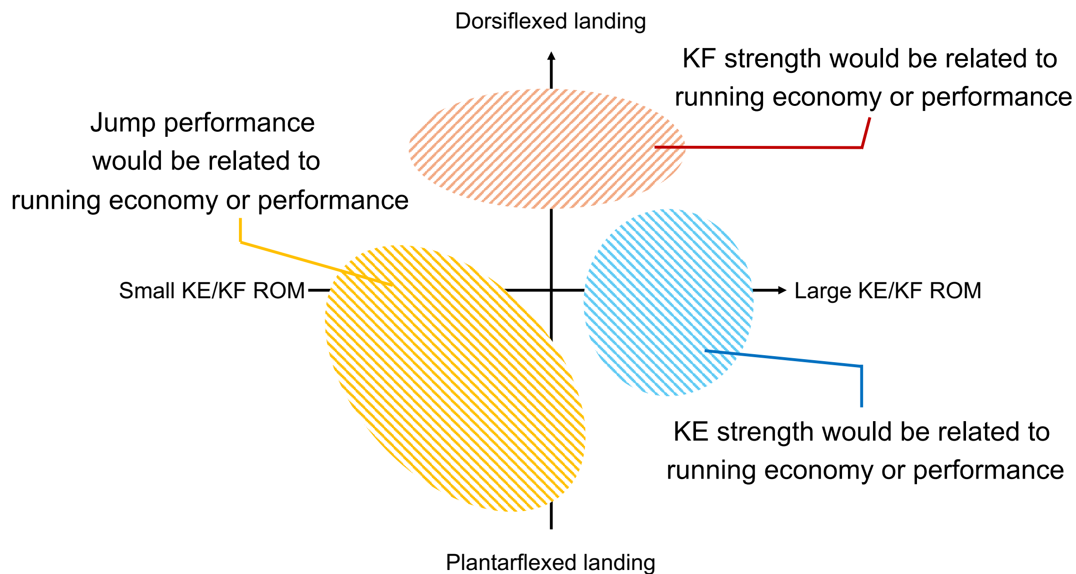


Figure 1-5. Hypothetical model of muscle function demands for better running economy and performance. For example, KF strength would be important for better running economy and performance in runners with large ankle dorsiflexion on the sagittal plane.
Abbreviations: KE, knee extension; KF, knee flexion; ROM, range of motion.

1-7. Knowledge gaps and purposes

From the two reviews, the following findings were obtained, respectively:

(1) Resistance training may induce greater benefits on running economy and potentially performance than plyometric training. Still, both modalities can be effective when delivered over more extended periods or when they promote neuromuscular adaptations, including via high-load resistance training or short ground-contact plyometric training, even in master runners.

(2) Relationships between muscle functions and both economy and performance would differ depending on when analyses are restricted to cohorts with shared kinematics (foot-strike angle and KE/KF ROM).

On the other hand, several knowledge gaps should be addressed:

(1) It has been unclear whether the effects of plyometric training on running economy and performance for master endurance runners (30–50 year-olds) are comparable with those of resistance training.

(2) It remains unknown whether the differences in running economy and performance responses to the training are primarily driven by improvements in muscle function or by kinematic profiles that distinguish runners into different clusters.

Given the work and household responsibilities of master endurance runners, it is crucial to identify effective and efficient adjunct training modalities to improve their running economy and performance. Although high-load resistance training has been shown to improve running economy effectively, its implementation requires specialized equipment and facilities, which may limit its practicality for many runners. Therefore, this doctoral thesis focuses on the effectiveness and

efficiency of plyometric training as a practical adjunct to daily running, and (1) evaluates its comparative effects with resistance training to clarify its efficacy in improving running economy and performance. Furthermore, this thesis (2) examines whether improvements in running economy and performance through plyometric training depend on muscle function itself or on running motion patterns that change which muscle functions become important.

To achieve these two aims, the thesis consists of five chapters (Figure 1-6):

Chapter 1: Effective training modalities, training variables, and the effects of adjunct training were clarified through a systematic review and meta-analysis. In addition, the potential effects of running kinematics on the relationships between muscular function and both running economy and performance were examined.

Chapter 2: Using a longitudinal design, the effects of plyometric training on running economy and performance, as well as their feasibility for master endurance runners, through comparing the effectiveness of resistance training, to achieve the first purpose.

Chapter 3: Runners were clustered by baseline running kinematics and tested whether the relationships between lower-limb muscle functions and both running economy and performance differ across kinematic profiles to clarify the second purpose.

Chapter 4: This chapter firstly identifies which adaptations are most strongly associated with improvements in running economy after plyometric training in non-clustered and clustered runners, as defined in Chapter 3. In addition, the magnitude of improvements in running economy was compared across kinematic clusters to reinforce the results obtained in Chapter 3.

Chapter 5: The results obtained so far were synthesized to identify the effectiveness of plyometric training and the way of enhancing the training effects for master endurance runners, and proposed profile-specific guidance, and explored their applicability beyond master endurance runners.

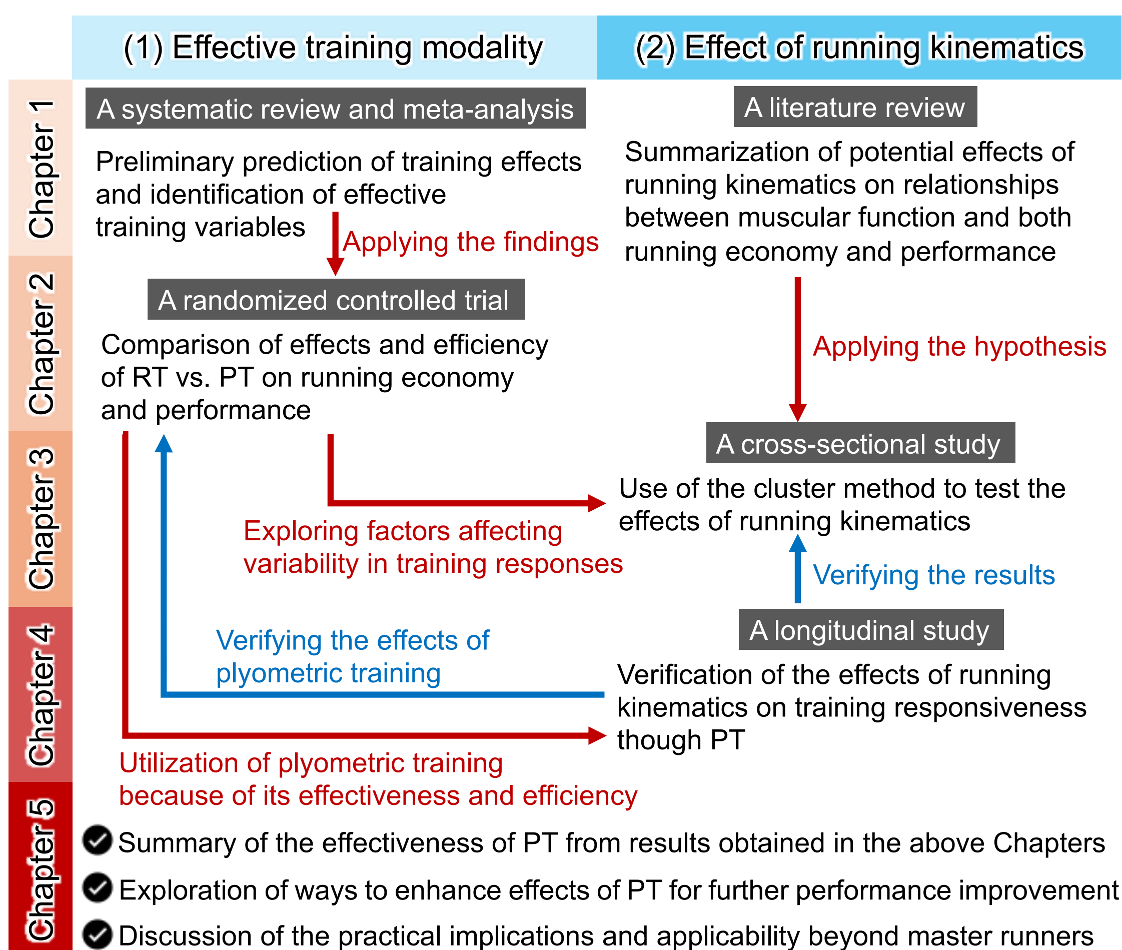


Figure 1-6. Overall framework of this doctoral thesis and relationships among chapters.

Abbreviations: RT, resistance training; PT, plyometric training

Chapter 2. Effects of Resistance vs. Plyometric Training on Running Economy and Performance in Master Endurance Runners: A Randomized Controlled Trial

2-1. Rationale and aims

In Chapter 1, a systematic review summarized the effects of resistance and plyometric training on running economy and performance. The findings suggested that resistance training, when performed alongside habitual running, can effectively improve running economy in endurance runners of mixed ages. However, its effects appear small among master endurance runners, and few studies have examined the efficacy of plyometric training in this age group. Although high-load resistance training has proven effective, its implementation requires specialized equipment and facilities, making it difficult for many runners to incorporate it into their daily routines. In contrast, plyometric training can be performed with minimal equipment and integrated more easily into regular running programs, providing a time-efficient and practical alternative for master endurance runners. Evidence also indicates that running economy may improve through longer interventions (regardless of frequency) or through neuromuscular adaptations elicited by high-load resistance training, while plyometric training emphasizing short ground-contact (fast SSC) actions may also promote efficiency gains. Nevertheless, the comparative effectiveness of resistance versus plyometric training could not be determined from the existing literature because intervention durations and training designs differed substantially among studies.

Thus, this study primarily examined the effectiveness of plyometric training, performed alongside habitual running, on improving running economy and performance among master endurance runners. To clarify its practical value, the effects of plyometric training were directly compared with those of high-load resistance training, which has traditionally been regarded as an effective but less feasible modality for this population. In addition to comparing overall training outcomes, this study aimed to determine the extent to which improvements in lower-limb muscle function, particularly muscle strength and reactive jump performance, are associated with changes in running economy and performance. It also sought to estimate the approximate contributions of changes in muscle function to improvements in running economy. The specific purposes were: (1) to verify whether plyometric training can serve as an effective and feasible adjunct training method for improving running economy and performance in master endurance runners, and (2) to clarify how improvements in muscle strength and jump performance mediate these adaptations.

2-2. Methods

2-2-1. Participants

Twenty-one endurance runners (7 females) with 10.1 ± 5.2 years of running training experience participated in the present study. Participants were asked to maintain their running training volume over the intervention period and to record their runs in a training log. Before the start of the present study, participants were informed of its purposes, risks, and benefits and signed an informed consent form. This study was approved by the Research Committee of Ritsumeikan University (BKC-

LSMH-2021-086). Participants were required to meet the following inclusion criteria: (1) age of 30–50 years, (2) had not experienced periodic (≥ 2 days per week) resistance or plyometric training within 6 months, (3) had run half- or full marathon within 2 years, (4) free from injury in the month preceding the study, and (5) had a running ≥ 2 days per week.

Participants were randomly allocated to either a resistance (n = 10, 3 females) or plyometric training (n = 11, 4 females) group, so that there were no significant differences in age, sex, running economy, $\dot{V}O_{2max}$, and 5-km running time at baseline by using the packages of "dplyr" and "sampling" in RStudio (version 2022.07.1+554, Boston MA). One runner in the plyometric training group dropped out of the intervention due to an injury during his daily running training. In total, 20 participants (resistance: n = 10, age = 43.8 ± 5.4 years; plyometric: n = 10, age = 41.4 ± 6.3 years) completed the study (Figure 2-1).

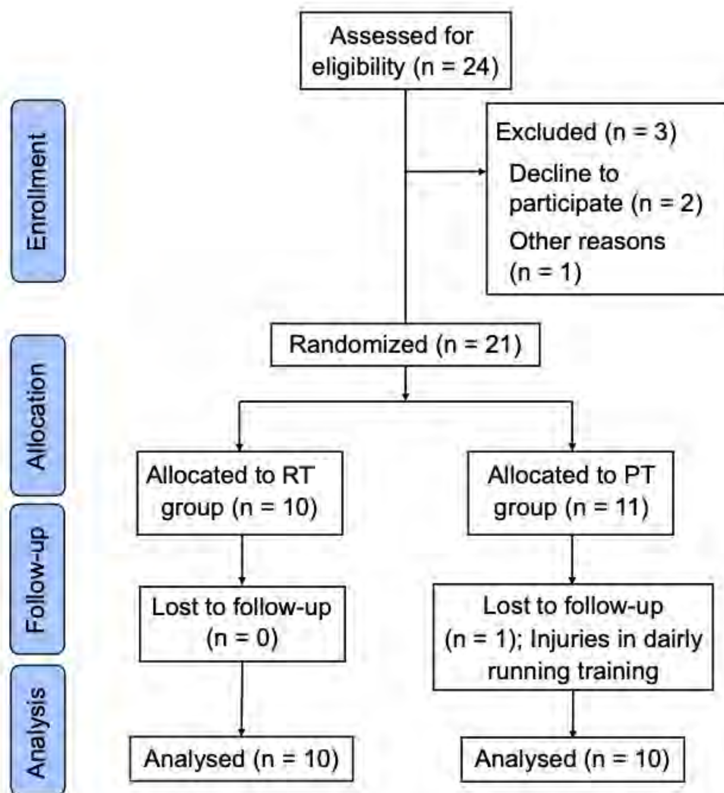


Figure 2-1. CONSORT diagram of the full recruitment and randomization process.

Abbreviations: RT, resistance training; PT, plyometric training.

This figure was modified from the study of Eihara et al. (2024) [121].

2-2-2. Study design

This study used a parallel, two-group, randomized, longitudinal experimental design to achieve the purposes of the present study. All participants performed the assigned training on two non-consecutive days per week for 10 weeks. The intervention period was set to 10 weeks because a recent review and Chapter 1 recommend a training period of 10 weeks or longer to achieve a larger improvement in running economy [92, 121]. The training frequency was set to twice per week, which was the most adopted frequency in previous studies summarized in Chapter 1. Moreover, the review indicated that training frequency itself does not substantially influence improvements in running economy, whereas longer intervention durations tend to produce greater effects.

All participants completed the following test battery in four experimental sessions: twice before (pre-test) and twice after (post-test) the training intervention. The measurements included body composition, 1RM of three lifting tasks, jump performance, running economy, and $\dot{V}O_{2max}$ on the first day, and a 5 km running time trial on the second day (at least 48 hours after the first day). The distance of 5 km for the time trial was chosen because (1) a 5-km running time is one of the predictors for marathon race time [122], and (2) in the practical field, runners often refer to a tool to predict marathon time from time trial records of shorter running distances [123]. Participants were asked to refrain from caffeine for three hours and alcohol for 24 hours before the first and second testing days and to wear the same shoes during the pre- and post-test. All tests were conducted at the same time of day (± 1.5 hours for each participant) to avoid circadian rhythm effects.

2-2-3. Measurements

Body composition. Height and body mass were measured with a fully automatic body scale with a stadiometer (WB-510, TANITA Corp., Tokyo, Japan). Body fat percentage and muscle mass were measured with a body composition analyzer (InBody770, InBody Japan Co., Ltd., Tokyo, Japan).

1RM. 1RM was measured for leg press (HS-SLP, Hammer Strength/Life Fitness, Illinois, USA), leg curl (Toredo, Senoh, Chiba, Japan), and calf raise (IMH703, Coming Health Tech, Qingdao, China). The participants commenced a warm-up of five repetitions at 50% of the estimated 1RM. After the warm-up, participants performed 3–6 trials to determine their actual 1RM by gradually increasing the load, with a 2-minute rest interval between trials [124]. The joint angles and success criteria for each 1RM test were as follows: for the leg press, initial joint angles for the knee and ankle were both at 90°, and participants sat deep in a chair. The trial was considered successful when the knees were fully extended. For the leg curl (in the prone position), the knees were first fully extended, and the heel collars of the shoes were placed at the center of the cushion. When the knees were fully flexed, the trial was successful. For the calf raise, the participants stood on a calf raise machine with the hip angle at 0°, knees fully extended, and ankles fully dorsiflexed. When the participants could plantarflex to the same height as that raised without a load (recorded beforehand), the trial was considered successful.

Jump performance. After the completion of the three 1RM tests, participants performed the counter-movement jump (CMJ) and 30-cm drop jump tests three times for each test. Before the tests, the

participants performed a warm-up consisting of static or dynamic stretching, followed by CMJ and drop jumps, performed three times each. For the CMJ test, participants performed a rapid downward squat followed by a vertical jump with an arm swing [125]. Jumping heights were recorded by using an optical measurement system (Opto-jump-next, Microgate, Bolzano, Italy). For the drop jump test, participants first stood on a 30-cm box, then stepped off the box to land and rebound-jump with an arm swing for maximum height with minimum ground contact time. Jump height, contact time, and drop jump index (jump height divided by contact time) were measured by using the optical measurement system. The best trial for each jump height was used for data analysis. If the highest jump heights in drop jumps were the same across two or three trials, the trial with the shortest ground contact time was adopted.

Running economy and $\dot{V}O_{2max}$. Running economy and $\dot{V}O_{2max}$ were measured using a treadmill (Valiant Ultra; Lode BV, Groningen, Netherlands) and a breath-by-breath gas analyzer (AE-310s, Minato Medical Science, Osaka, Japan). Heart rate was also assessed using a heart rate sensor (Polar H10, Polar, Kempele, Finland). Before the test session, the gas analyzer was calibrated with gases of known concentration (16% O_2 and 5% CO_2). The participants warmed up on the treadmill at 8 km/h for 5 minutes, rested for 3 minutes, and then ran for 3 minutes at 8, 10, and 12 km/h. Running economy was calculated as the average oxygen cost (mL/kg/km) during the final minute at each running speed.

Following the submaximal running test, the participants rested for 3 minutes and underwent an incremental test to determine $\dot{V}O_{2max}$. The treadmill speed was first set to 12 km/h, then increased

by 1 km/h every 1 minute, and then by 0.6 km/h every 1 minute from 14 km/h until exhaustion, defined as the point at which the participant could no longer run at the required velocity. The following criteria were used for the attainment of $\dot{V}O_{2max}$: heart rate greater than 90% of age-predicted maximal heart rate (208 - runners' age × 0.7); and RER ≥ 1.10 [126]. $\dot{V}O_{2max}$ was determined as the highest $\dot{V}O_2$ value using a 30-second moving window. These running protocols were performed under similar environmental conditions (22–24°C) between the pre- and post-test.

5-km running time. On the second trial day, a 5 km running time trial was performed on a 400 m track. The time trial was conducted at 7:00–9:00 or 18:00–21:00, with the same time zone used for the pre- and post-test for each participant. Following a self-selected 30-minute warm-up consisting of jogging and stretching, participants performed a 5 km time-trial run. Verbal encouragement was provided throughout the test. The 5 km running time was recorded using a system stopwatch (SVAS011, Seiko Watch, Tokyo, Japan). Atmospheric temperature and humidity were measured using a digital thermo-hygrometer (WBGT-213B, Kyoto Electronics Manufacturing, Kyoto, Japan). When the temperature exceeded 28 °C, participants were asked at the end of each lap whether they felt able to continue running to minimize the risk of heat-related illness. Three participants (resistance training group = 2, plyometric training group = 1) did not complete the 5 km running time trial in the post-test based on these criteria. Thus, the sample sizes of this variable were 8 and 9 for the resistance and plyometric training groups, respectively.

Training intervention. Both groups performed prescribed training programs (Table 2-1) consisting of 2 sessions per week for 10 weeks, with at least 48 hours between sessions. The participants were instructed to maintain regular running training but to refrain from running within 6 hours, and to conduct additional plyometric or resistance training sessions to avoid the influence of fatigue and potential interference effects [127, 128]. The resistance and plyometric training programs were conducted according to their group allocation. All training sessions were supervised. At the end of each training session, the rate of perceived exertion (RPE) was assessed for the legs and the whole body using the Borg CR10 scale [129].

For resistance training, the training was performed without counter-movement actions, with 2 seconds for each concentric and eccentric phase, under the guidance of a metronome (60 bpm). Two-minute rest intervals were taken in between sets. These training programs were developed based on previous studies [35, 62, 67, 68, 92, 130] and the results from Chapter 1. For plyometric training, the participants were instructed to jump explosively with minimum ground contact time (except for CMJ) and maximum jump height. Ground contact time was monitored using a mat-switch platform system (Multi jump tester, DKH, Tokyo, Japan), and participants received instant feedback to perform jumps with a ground contact time ≤ 300 ms.

Table 2-1. Training programs in resistance and plyometric training.

Resistance	Week 1–2	Week 3–4	Week 5–6	Week 7–8	Week 9–10
Leg press, leg curl, and calf raise	50–60% 1RM 3 sets × 10 reps	75% 1RM 3 sets × 8 reps	80% 1RM 3 sets × 6 reps	85% 1RM 3 sets × 5 reps	90% 1RM 3 sets × 4 reps
Plyometric	**Week 1–2**	**Week 3–4**	**Week 5–6**	**Week 7–8**	**Week 9–10**
CMJ	3 sets × 8–10 reps				
3RJ	6–8 sets				
BL hurdle hop	3 sets × 8–10 reps	4 sets × 8–9 reps	4 sets × 10 reps		
20 cm DJ		3 × 8–9 reps	3 sets × 10 reps		
5RJ		4–5 sets	6 sets	6–7 sets	8 sets
SL hurdle hop				4 sets × 8–9 reps	4 sets × 10 reps
30 cm DJ				3 sets × 8–9 reps	3 sets × 10 reps

Abbreviations: 1RM, one repetition maximum; CMJ, counter-movement jump; reps, repetitions; DJ, drop jump; RJ, rebound jump (e.g., 3RJ, three rebound jump); BL, both legs; SL, single leg.

This table was modified from the study of Eihara et al. (2024) [121].

2-2-4. Statistical analyses

Twenty runners (10 per group) completed more than 90% of their prescribed training sessions and were included in the analysis. Descriptive data are presented as means and SDs. Statistical analyses were performed using RStudio (version 2022.07.1+554, Boston, MA). Statistical significance was set at $P < 0.05$. The normality of distribution was tested using Shapiro-Wilk test, and all variables were confirmed as normally distributed. The RPE of training was averaged across all training sessions, and the group differences were tested using an independent *t*-test. Regarding the variables measured at the pre- and post-test, all except the oxygen cost of running were analyzed using a linear mixed model (LMM) with group and time as fixed effects. When a significant group-by-time interaction was found in an LMM, 1) a paired *t*-test was performed for the pre- and post-test values within each group, and 2) absolute change values were calculated and compared between groups by an unpaired *t*-test, as post-hoc tests. For the oxygen cost of running, a repeated 3-way ANOVA (group, time, and running velocity) was performed. Hedges' *g* values were calculated to estimate the magnitude of changes in outcomes between the pre- and post-test in each group and were interpreted as trivial ≤ 0.20, small 0.20–0.49, moderate 0.50–0.99, and large ≥ 1.00 (regardless of its sign, negative or positive [89]). To improve the statistical inference, the mean difference from baseline with a bootstrap 95% CI (5000 samples, bias-corrected and accelerated) was calculated for each of the primary training outcomes (1RM, jump, and aerobic parameters) by using estimation statistics [131]. In addition, within-participant repeated-measures correlations were performed using the R package "rmcorr" to assess the common intra-individual association between changes in the main training outcomes (running performance-related variables vs. muscle function; and running economy vs. 5-km running time) within each group [132]. The *P*-value was adjusted by using the Benjamini-Hochberg method.

In addition, the standard deviation of individual responses (SD_{IR}) was calculated in accordance with a previous study: $SD_{IR} = \sqrt{(SD_{exp})^2 - (SD_{con})^2}$, where SD_{exp} was the SD of the changes in a variable in an experimental group, and SD_{con} was the SD of the changes in a variable in a control group. As the present study did not include a control group, SD_{con} was calculated from the data to verify reproducibility. The data included 21 male runners (30–48 years old) on the oxygen cost of running. SD_{IR} was interpreted as small ≤ 0.2, moderate 0.2–0.6, large 0.6–1.2, very large 1.2–2.0, extremely large ≥ 4.0 [133].

2-3. Results

2-3-1. Changes in variables and their variation in the running economy improvement

There were no significant differences between the two groups (independent *t*-tests) on any baseline variables. Anthropometric, physiological, and running data are shown in Table 2-2. The average of RPE across all sessions was significantly lower for the plyometric training (leg: 3.5 ± 1.4, whole body: 3.4 ± 1.1, $P < 0.001$) than for the resistance training group (leg: 5.7 ± 1.6, whole body: 4.7 ± 1.9, $P < 0.001$). In addition, training duration was significantly shorter during plyometric training than during resistance training (17.1 ± 2.2 min/session vs. 23.9 ± 2.0 min/session, $P < 0.001$). There were no significant changes in height, body mass, body fat percentage, muscle mass, and $\dot{V}O_{2max}$ in both groups ($P = 0.079$–0.896; Table 2-2). Weekly running training volume had a significant main effect of time (resistance: 37.5 ± 1.1 km/week to 28.5 ± 1.0 km/week; plyometric: 44.8 ± 22.8 km/week to 43.1 ± 18.6 km/week, $P = 0.010$) with no significant main effect of group ($P = 0.124$) and interaction ($P = 0.117$), indicating that both groups reduced running training volume during the intervention period compared to before the intervention.

Table 2-2. The changes of characteristics of participants from pre- to post-intervention.

	Resistance training group (n = 10)			Plyometric training group (n = 10)		
	Pre	Post	*g*	Pre	Post	*g*
Height (m)	1.67 ± 0.08	1.67 ± 0.08	0.01	1.68 ± 0.10	1.68 ± 0.10	0.02
Body mass (kg)	58.3 ± 9.3	58.4 ± 9.5	0.01	61.4 ± 14.2	61.6 ± 14.7	0.01
Body fat percentage (%)	18.0 ± 6.6	17.0 ± 5.4	-0.16	18.2 ± 5.4	17.3 ± 6.0	-0.15
Muscle mass (kg)	45.1 ± 8.8	45.7 ± 8.7	0.07	46.9 ± 9.5	47.6 ± 10.2	0.07
$\dot{V}O_{2max}$ (mL/kg/min)	47.3 ± 6.7	47.3 ± 5.8	-0.04	46.5 ± 8.2	46.0 ± 6.3	-0.08

The values were mean ± SD. Hedges' *g* was calculated from the change from pre- to post-test.

This table was modified from the study of Eihara et al. (2024) [121].

Significant group-by-time interactions were found in all 1RM tests (*P* = 0.001–0.017). Plyometric training significantly increased the 1RM of leg curl (*P* = 0.007) but not leg press and calf raise (*P* = 0.372–0.774), whereas resistance training significantly increased the 1RM values of the three lifting tasks after the intervention (*P* < 0.001; Figure 2-2). Significant main effects of time were observed for all jump performance variables (*P* = 0.005–0.016) without group-by-time interactions (*P* = 0.248–0.603; Figure 2-2), indicating significant increases in all jump performances for both groups, without a significant group difference.

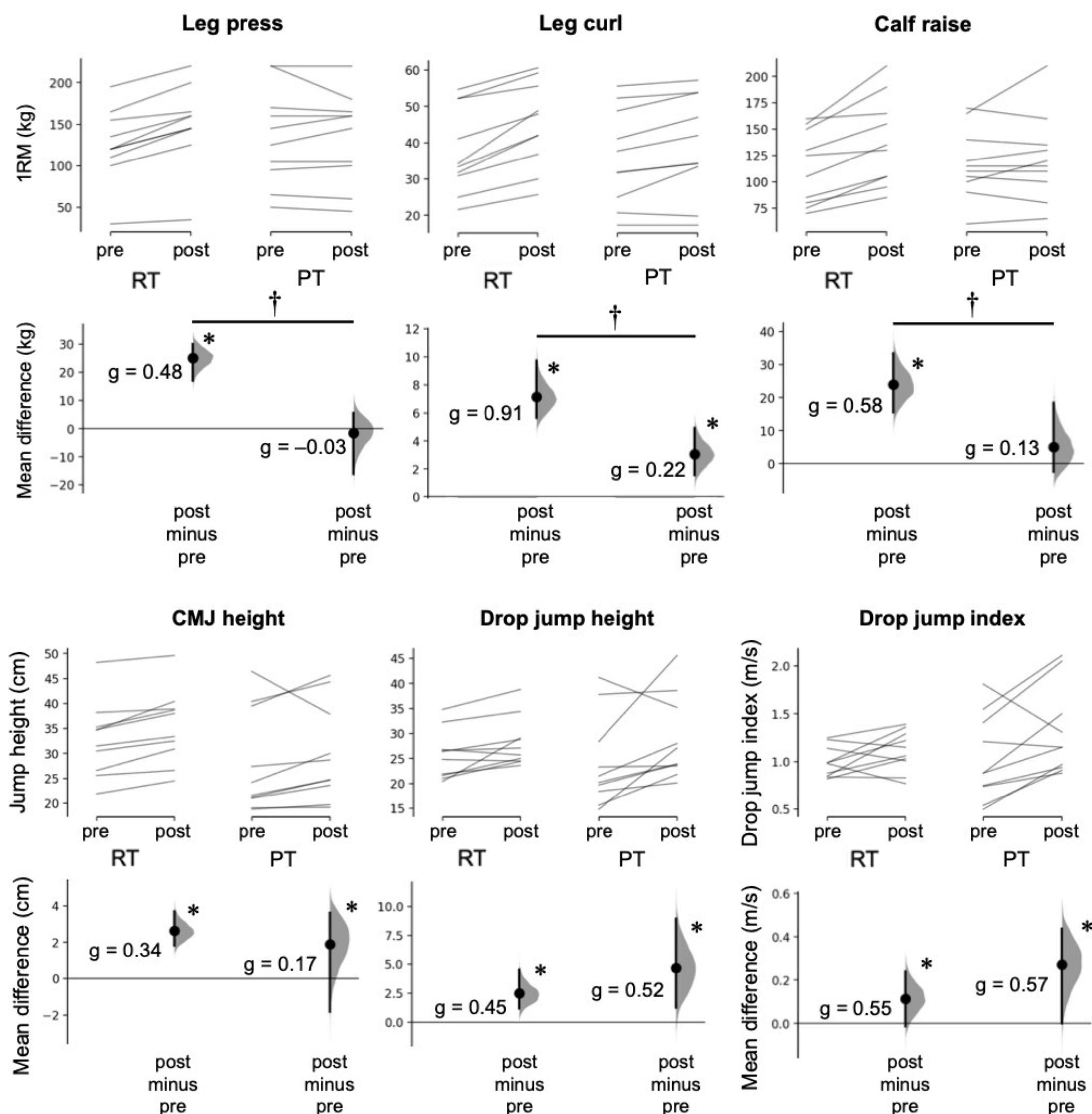


Figure 2-2. Changes in 1RM of the three lifting tasks and jump performances after the training in the resistance and plyometric groups. In each subfigure, the raw data is plotted on the upper axes for plyometric (left) and resistance training (right); each paired set of observations at the pre- and post-test is connected by a line. On the lower axis, each paired mean difference is plotted as a bootstrap sampling distribution. Mean differences are depicted as dots with horizontal dashed lines; 95% CIs are indicated by the ends of the vertical error bars. Hedges' *g* represents the magnitude of the changes in the variables from pre to post.

* denotes a significant change from pre to post ($P < 0.05$).

† denotes a significant difference between groups ($P < 0.05$).

Abbreviations: RT, resistance training; PT, plyometric training.

This figure was modified from the study of Eihara et al. (2024) [121].

The SD_{IR} for the oxygen cost of running was 3.08, suggesting that the individual variation in the training effects on the oxygen cost of running was very large. A repeated 3-way ANOVA regarding the oxygen cost of running showed a significant main effect of time and running velocity ($P = 0.001$ and 0.008, respectively), without a main effect of group or any interactions ($P = 0.234$–0.881; Figure 2-3), indicating that both groups similarly reduced oxygen cost (improved running economy) regardless of running velocity (resistance training: 1.33%; plyometric training: 2.73%). No significant main effects or group-by-time interactions were detected in the 5-km running time trial performance ($P = 0.491$–0.745; Figure 2-3).

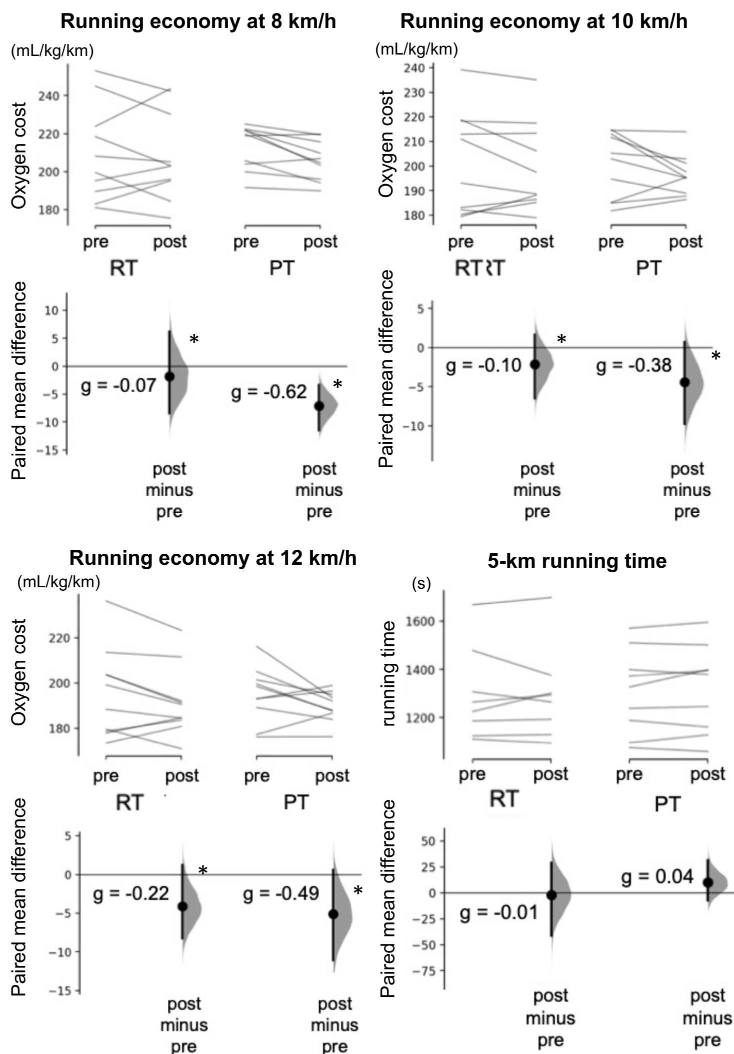


Figure 2-3. Changes in oxygen cost of running (running economy) at 8, 10, 12 km/h, and 5-km running time after the training in the resistance and plyometric training group. In each subfigure, the raw data is plotted on the upper axes for plyometric (left) and resistance training (right); each paired set of observations at the pre- and post-test is connected by a line. On the lower axis, each paired mean difference is plotted as a bootstrap sampling distribution. Mean differences are depicted as dots with horizontal dashed lines; 95% CIs are indicated by the ends of the vertical error bars. Hedges' *g* represents the magnitude of the changes in the variables from pre to post. * denotes a significant change from pre to post ($P < 0.05$).

Abbreviations: RT, resistance training; PT, plyometric training.

This figure was modified from the study of Eihara et al. (2024) [121].

2-3-2. Associations between muscle functions and running economy/performance

Resistance training. A significant correlation was found between training-induced changes in calf raise 1RM normalized to body mass and oxygen cost of running (averaged across 8–12 km/h, r = -0.805, P = 0.030; Table 2-3) but not between the other measured variables (r = -0.692 to -0.499, P = 0.052–0.251) in the resistance training group. In contrast, there are no significant relationships between the changes in muscle functions and 5-km running time (r = -0.682 to -0.317, P = 0.006–0.456).

Plyometric training. There were no significant relationships between the changes in muscular functions and oxygen cost of running (averaged across 8–12 km/h, r = -0.499 to -0.092, P = 0.320–0.789) nor 5-km running time (r = -0.462 to 0.004, P = 0.208–0.991; Table 2-3) in the plyometric training group.

Table 2-3. The correlation between the changes in aerobic working capacities (oxygen cost of running averaged across 8–12 km/h and 5-km running time) and muscle function (1RM normalized to body mass and jump performances) in each group.

	Resistance training group		Plyometric training group	
Associations with oxygen cost of running				
Leg curl 1RM	*r* = -0.660	*P* = 0.052	*r* = -0.361	*P* = 0.368
Leg press 1RM	*r* = -0.585	*P* = 0.131	*r* = -0.174	*P* = 0.665
Calf raise 1RM	***r* = -0.805**	***P* = 0.030 ***	*r* = -0.092	*P* = 0.789
CMJ height	*r* = -0.499	*P* = 0.177	*r* = -0.334	*P* = 0.379
DJ height	*r* = -0.692	*P* = 0.172	*r* = -0.476	*P* = 0.322
DJ index	*r* = -0.562	*P* = 0.251	*r* = -0.499	*P* = 0.320
Associations with 5-km running time				
Leg curl 1RM	*r* = -0.615	*P* = 0.106	*r* = -0.042	*P* = 0.984
Leg press 1RM	*r* = -0.682	*P* = 0.006	*r* = 0.004	*P* = 0.991
Calf raise 1RM	*r* = -0.511	*P* = 0.178	*r* = -0.190	*P* = 0.693
CMJ height	*r* = -0.323	*P* = 0.456	*r* = -0.425	*P* = 0.246
DJ height	*r* = -0.317	*P* = 0.456	*r* = -0.462	*P* = 0.208
DJ index	*r* = -0.533	*P* = 0.182	*r* = -0.453	*P* = 0.245

Abbreviations: 1RM, one repetition maximum; CMJ, counter-movement jump; DJ, drop jump.

* denotes a significant correlation between variables ($P < 0.05$).

2-3-3. Associations between running economy and performance

There was a significant relationship between changes in oxygen cost of running and 5-km running time (r = 0.512, P = 0.030; Figure 2-4), suggesting that improvements in running economy can translate into enhanced running performance.

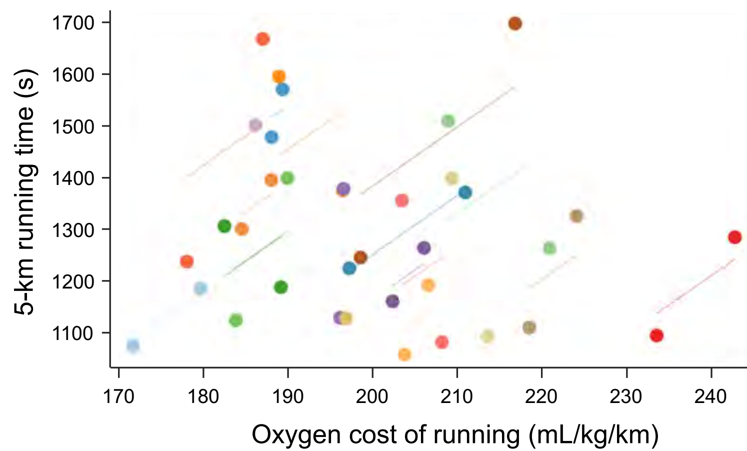


Figure 2-4. The correlation coefficients between the changes in oxygen cost of running and 5-km running time together with both groups.

2-4. Discussion

To the best of our knowledge, this is the first study to directly compare the effectiveness of resistance and plyometric training, performed as adjuncts to daily running, on running economy and performance in master endurance runners. One of the main findings was that plyometric training, despite its shorter session duration and greater practicality, was equally effective as high-load resistance training in improving running economy, although neither training modality led to significant improvements in 5-km running time. In contrast, the improvements in running economy observed after plyometric training occurred independently of changes in maximal muscle strength or jump performance, suggesting that enhanced neuromuscular efficiency rather than large gains in force capacity may underlie its benefits. Collectively, these results indicate that plyometric training represents a practical and effective alternative to resistance training for improving running economy in master endurance runners, particularly when time, equipment, or access to facilities is limited.

In the present study, plyometric training significantly increased CMJ height and drop-jump performance, and resistance training increased 1RM for the three lifting tasks and jump performance (Figure 2-2). This is reasonable based on the training specificity of both training modalities [52] and some transferring effects of resistance training (i.e., resistance training can improve jump performance [67]). Several previous studies suggest that increasing muscle strength and jump performance would improve long-distance running performance [18, 45, 134]. The present study found a significant relationship between resistance-training-induced changes in the calf raise 1RM and running economy. A previous study found that the triceps surae makes a considerable contribution to the vertical support impulse that accelerates the body upward during running [105, 135]. Interestingly, however, the plyometric training group did not show a significant relationship between muscle function (e.g., calf raise 1RM) and improvements in running performance. This is because resistance training groups would enhance running

economy primarily via improvements in maximal strength and neuromuscular efficiency, while plyometric training could exert its effect through improvements in the utilization of the SSC during stance phases and possibly coordination [34]. On the other hand, no significant relationships between jump performance enhancement and running performance improvements were observed. This result may indicate that the running motion in this study did not substantially rely on jump-related capabilities. Instead, deeper neuromuscular and muscle-tendon stiffness adaptations, rather than superficial SSC performance, played a more critical role. Given that the importance of SSC ability varies depending on running mechanics [40, 109, 110], future research should focus on training responsiveness across different running motion patterns.

Significant improvements in running economy were found for both resistance and plyometric training (Figure 3). In particular, the improvement in running economy induced by plyometric training (2.0–3.4%, effect size: g = -0.38 to -0.62 “small-to-moderate”) was larger than that in our recent review (< 1%, g = -0.13 [95% CIs -0.47 to 0.21]) [121]. Moreover, the improvement in running economy in the plyometric training group may be meaningful, as a 2.4% improvement has been reported [18]. Two potential explanations for the meaningful versus trivial effects of plyometric training observed in the current study, compared with previous studies, can be offered. First, recent studies have suggested that a more extended training period for resistance and plyometric training facilitates improvements in running economy [92, 121]. Thus, the current research conducted plyometric training for 10 weeks, which is longer than the training periods used in most previous studies (see the review [121]). Second, the jump training is advised to be performed with a ground contact time comparable to that during running (i.e., 200–300 ms [105]). The ground contact time during jump training was therefore monitored, and participants in the plyometric training group of the present study performed the jumps within 300 ms of ground contact in 98% of training sessions. Furthermore, the RPEs during the training for the leg and whole body were both

significantly lower in the plyometric training than in the resistance training group, which is of great practical importance. Collectively, plyometric training can be considered a relatively easily implemented yet similarly effective training modality compared to resistance training for improving running economy in master endurance runners [67].

Neither group improved their 5-km running time despite improvements in running economy. This may partly be because running performance was measured only in the 5-km time-trial condition, leading to a mismatch in running velocity between the measurements of running economy and performance. More specifically, the average running velocity during the 5-km running time trial in this study was 13.9 km/h, which is higher than the velocities (8–12 km/h) at which running economy was measured in this study. Nevertheless, runners who improved their running economy through the intervention tended to shorten their 5-km running time in the present study. This suggests that the benefits of improved running economy might be more pronounced over longer distances, where running velocities are typically lower and more closely aligned with those used in economy testing. Indeed, previous studies have reported stronger associations between running economy and performance at longer distances [14, 136-139]. Hence, it is recommended that future studies assess running economy and performance across a broader range of distances and running velocities, enabling a more comprehensive evaluation of the effects of training interventions and their relationship with performance and other physiological outcomes.

It may be of practical relevance that both training groups reduced their running volume during the training intervention, even though the participants were asked to maintain their daily running volume. This is likely because it was challenging for them to keep the running volume while attending the university to participate in the training intervention (resistance: 23.9 ± 1.1 min/session; plyometric: 20.2 ± 1.5 min/session), in combination with their daily work schedules. However, previous studies have found that resistance training in parallel with running training was successful in improving running economy and 10-

km running time despite a 40-58% reduction in daily running volume [73, 76]. The training effects on running economy and 5-km running time were also retrospectively assessed using ANCOVA, while accounting for running volume, but no significant effects were detected. Thus, a reduction in running volume would not significantly influence our main findings. Nevertheless, running training programs should also be carefully monitored and adjusted in future studies to better understand their interactions with strength-based adjunct training and running training.

There were three limitations in this study. Although the total workload and mechanical stress applied to the muscles were not strictly matched between the resistance and plyometric training interventions, this limitation was acknowledged in the present study. To compensate for this discrepancy, subjective exercise intensity and total training duration were compared between groups. Both indices were consistently lower in the plyometric training group, indicating higher training efficiency. In addition, this study did not include a control group; however, reproducibility data from prior measurements showed a typical error (TE) of 1.45%. Considering that the present study observed improvements of 1.33% in the resistance training group and 2.73% in the plyometric training group, the magnitude of change clearly exceeds the TE, particularly in the plyometric training group. This finding reinforces the effectiveness and practical relevance of plyometric training for improving running economy and performance in master endurance runners. Finally, the study was conducted from February (late winter) to May (early summer), and from May to August (late summer), during which the ambient temperature gradually increased. Even under these potentially unfavorable conditions for endurance performance, the 5-km time did not deteriorate after training. This observation further supports the idea that the training interventions produced beneficial effects that counteracted the negative effects of heat stress.

2-5. Summary

As an adjunct exercise program to daily running, plyometric training was found to be an effective method for improving running economy in master endurance runners, comparable to high-load resistance training. However, neither training modality resulted in significant improvements in 5-km running performance, suggesting that further research focusing on longer-distance performance and prolonged interventions is warranted. Importantly, plyometric training required lower perceived fatigue and could be performed without specialized equipment or machines, thereby enhancing its practical feasibility for this population. Considering these advantages, plyometric training appears to be a time-efficient and accessible alternative to resistance training for improving running economy in master endurance runners. Finally, training-specific relationships between improvements in distinct muscle functions and changes in running economy and performance were observed, suggesting that modality-dependent neuromuscular adaptations may underlie these improvements.

Chapter 3. Classifying Master Endurance Runners Based on Running Kinematics Strengthens Relationships Between Muscle Function and Both Running Economy and Performance

3-1. Rationale and aims

Chapter 2 demonstrated that plyometric training can effectively and efficiently improve running economy, yielding benefits comparable to (or in some cases greater than) those of resistance training. In the resistance training group, improvements in running economy were correlated with increases in calf raise 1RM strength, whereas no significant associations were observed between changes in jump performance and running economy or performance in the plyometric training group. These findings highlight that training responsiveness and the relative importance of muscle functions (e.g., SSC ability) may not uniform across individuals. Given this variability, it is crucial to determine which runners benefit most from plyometric training modality and to identify the physiological and biomechanical factors that underlie these differential adaptations.

One possible explanation is that differences in running kinematics influence how muscle function contributes to improvements in running economy. Biomechanically, the plantarflexors play a key role in propulsion by increasing leg stiffness and enabling efficient SSC utilization. Runners exhibiting small KE/KF ROM or forefoot strike patterns may rely more on the lower-leg SSC function. Conversely, runners with a dorsiflexed foot-strike (rearfoot pattern) tend to show higher biceps femoris activation, while those with a large KE/KF ROM more actively recruit the rectus femoris during the propulsion [39-41, 113]. These findings collectively suggest that running kinematic profile modulates which muscle groups primarily contribute to propulsion and energy efficiency (see the Figure 1-5).

To operationalize this idea, k-means clustering was used to group endurance runners based on foot-strike angle and KE/KF ROM measured at a common absolute velocity [140, 141]. K-means clustering classifies data based on distributional geometry by minimizing within-cluster variance, allowing the meaningful subgroups that better capture continuous variations in running kinematics. Associations between muscle function and running economy/performance were then examined in the full cohort and within clusters under both a common absolute velocity and a common relative velocity (e.g., 80% of velocity of $\dot{V}O_{2max}$ [$v\dot{V}O_{2max}$]). Accordingly, the primary aim of this chapter was to determine, by kinematic profile, which muscle strength and jump performances are most closely related to running economy and performance. It was hypothesized that relationships would be stronger within clusters than in the non-clustered cohort, at least under absolute-speed evaluations. For example, KF strength should be associated with running economy and performance in dorsiflexed rearfoot runners, whereas KE strength should weigh more heavily in runners characterized by large KE/KF ROM.

3-2. Methods

3-2-1. Participants

Fifty-nine endurance male runners voluntarily participated in this study (Table 3-1). Participants were required to meet the following inclusion criteria: (1) age of 30–50 years, (2) a seasonal record over 5 km or longer race with WA points of > 54 (e.g., full-marathon record < 4:00:05)[142], (3) had a body mass index < 24 kg/m^2, (4) free from moderate injuries in the three months and minor injuries in the month preceding the study, and (5) had a running ≥ two days per week in the three months. Running performance was represented as the WA score. This study was approved by the ethics committee of Ritsumeikan University (BKC-LSMH-2023-011), and all procedures used in this study were conducted in accordance with the

Declaration of Helsinki. Before the experiments, all participants were fully informed of the purpose and risks of the experiment and provided written consent.

Table 3-1. The characteristics of participants.

	Mean ± SD
Age (yrs)	40.1 ± 6.0
Height (m)	1.71 ± 0.06
Body mass (kg)	60.9 ± 6.4
Fat percentage (%)	11.4 ± 3.8
Seasonal record (h:min:sec)	2:57:49 ± 23:49
Energy cost at 11 km/h (kcal/kg$^{0.915}$/km)	1.48 ± 0.13
Energy cost at 80% v$\dot{V}O_{2max}$ (kcal/kg$^{0.839}$/km)	1.96 ± 0.13
$\dot{V}O_{2max}$ (mL/kg/min)	54.0 ± 5.3
v$\dot{V}O_{2max}$ (km/h)	17.7 ± 1.6

The seasonal record over distances from 5000 m to the ultra-marathon (100 km) was converted to an equivalent full-marathon time.

3-2-2. Procedure

Participants visited the laboratory on two occasions, separated by 24–168 hours. All tests were completed at 22℃ (21.0–22.7℃). Participants were instructed to avoid strenuous exercise and alcohol for 24 hours and caffeine for 6 hours before testing. In the first session, participants were involved in measurements of body composition, KE/KF strength, jump performance, and $\dot{V}O_{2max}$. Body composition data, running kinematics, and the energy cost of running (running economy) were measured during the second session. A seasonal record was obtained within a year for each participant from the official record. Body composition data were assessed in both sessions and used to scale $\dot{V}O_{2max}$ and to normalize the energy cost of running on the first and second days, respectively.

Body composition. Height and body mass were measured with a fully automatic body scale with a stadiometer (WB-510, TANITA Corp., Tokyo, Japan). Body fat percentage, muscle mass, and fat-free mass were measured with a body composition analyzer (InBody770, InBody Japan Co., Ltd., Tokyo, Japan).

Knee extension (KE)/flexion (KF) torque. The isokinetic KE/KF concentric torque of the right leg was assessed in a seated position (hip angle at 90°) using a dynamometer (Biodex System IV, Biodex Medical Systems, Shirley, NY). Participants were instructed to sit deeply in the seat, place their hands on the handrail, and secure their upper body with a belt to prevent extraneous movement. The seat was adjusted to align the lateral tibial condyle with the rotation center of the attachment. Participants first performed a warm-up consisting of isometric KE/KF at 90° of knee joint angle, with three repetitions at 50%, 70%, and 90% of maximal effort. Then, they practiced two isokinetic concentric contractions in each of slow (30°/s) and fast (180°/s) conditions in 2–3 round trips from 90° to 0° (full extension) of the knee joint angle at

50% of their maximal effort. Finally, maximal isokinetic KE/KF concentric torque was measured in two round trips in each isokinetic velocity with a rest period of 60 seconds. The best trial for each KE and KF torque in the range of motion was selected for data analysis.

Jump performance. Participants performed the CMJ, 30-cm drop jump, and three rebound jump tests three times for each test. For the CMJ test, participants performed a rapid downward squat followed by a vertical jump with an arm swing. Jump height was recorded using an optical measurement system (Opto-jump-next, Microgate, Bolzano, Italy). The best trial for jump height was used for data analysis. For the drop jump test, participants first stood on a 30-cm box and then stepped off the box to land and rebound-jump with an arm swing for maximum height with minimal ground contact time. Three rebound jumps involved participants performing three vertical jumps with an arm swing to maximize height while minimizing ground contact time. The optical measurement system measured jump height, contact time, and drop/rebound jump index (jump height divided by contact time). The best trial for the jump index was used for data analysis. If the highest jump indices were the same for two or three trials, the trial with the highest jump height was adopted.

$\dot{V}O_{2max}$. $\dot{V}O_{2max}$ was measured using a treadmill (Valiant Ultra; Lode BV, Groningen, Netherlands), breath-by-breath gas analyzer (AE-310s, Minato Medical Science, Osaka, Japan), and mask (AMA104 and AMA512, Minato Medical Science, Osaka, Japan). Heart rate was also assessed using a heart rate sensor (Polar H10, Polar, Kempele, Finland). Before the test session, the gas analyzer was calibrated with gases of known concentration (16% O_2 and 5% CO_2). As a warm-up, participants ran on the treadmill at 8 and 11 km/h for 4 minutes each, with a 2-minute rest between them. The 2-minute rest period comprised a 1-minute walk at 3.2 km/h and a 1-minute passive rest. The participants then rested for 2 minutes and

underwent an incremental test to determine $\dot{V}O_{2max}$. The treadmill speed was first set to 8 km/h and increased by 1 km/h every 1 minute, then by 0.6 km/h every 1 minute from 14 km/h until exhaustion, which was defined as the point at which the participant could no longer run at the required velocity. If runners did not reach exhaustion, the following criteria were used for the attainment of $\dot{V}O_{2max}$: heart rate greater than 90% of age-predicted maximal heart rate (220 – runners' age); RER greater than 1.10 [24]; and not observing an increase of more than 1 mL/kg/min of $\dot{V}O_2$ at a stage [143]. $\dot{V}O_{2max}$ was determined as the highest $\dot{V}O_2$ value using a 30-second moving window. When participants could not complete the entire final stage (< 1-minute), $v\dot{V}O_{2max}$ was calculated as the fractional time reached in the final stage multiplied by the increment rate [67]. For example, if a runner finished the increment run for 30 seconds at 13 km/h, $v\dot{V}O_{2max}$ is 13.5 km/h (13 [velocity of the final stage] + 1 [increment rate] × 30/60 [fractional time]).

Energy cost and allometric scaling. In the second session, the energy cost of running was measured using a 0%-gradient treadmill (Integrity SL Console; Life Fitness, Illinois, USA) with the same gas analyzer and mask as for the $\dot{V}O_{2max}$ measurement. The participants ran for 4 minutes at 8 km/h as a warm-up, and then at 11 km/h and 80% of $v\dot{V}O_{2max}$ for 4 minutes for each velocity. 11 km/h was chosen for assessing the energy cost of running because all runners in a previous study (n = 97) could run with RER ≤ 1.00 at this velocity [32]. 80% of $v\dot{V}O_{2max}$ was adopted because runners can theoretically continue running at this velocity without breaks for more than 2 hours [33], and it can predict a 16 km running time [144]. The energy cost of running was calculated as the average energy cost during the final minute at each running velocity. The energy cost of running was calculated from the average second-by-second $\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute. Updated nonprotein respiratory quotient equations [145] were used to estimate substrate use (g/min) during the monitored period. Energy derived from each substrate was then calculated

by multiplying fat and carbohydrate usage by 9.75 and 4.07 kcal, respectively, reflecting the average energy content of metabolized substrates during moderate- to high-intensity exercise [146]. Finally, the energy cost of running was expressed as the total energy expenditure per kilometer (kcal/km). The energy cost of running was allometrically adjusted by body mass. The allometric exponent was calculated by transforming the equation [147]: $B = aM^b$ into a logarithmic form $Log(B) = Log(a) + b\,Log(M)$, where B is the metabolic rate, a is a constant, M is the body mass, and b is the allometric exponent. Allometric exponent was obtained for all participants as b = 0.915 (kcal/kg$^{0.915}$/km) for the energy cost of running at 11 km/h and b = 0.839 (kcal/kg$^{0.839}$/km) for that at 80% of $v\dot{V}O_{2max}$ (Appendix B).

Running kinematics. Reflective markers were positioned at 32 locations. Three-dimensional data during running at 11 km/h and 80% of $v\dot{V}O_{2max}$ were captured using Cortex software (Motion Analysis Corporation, Santa Rosa, CA) with a motion analysis system comprising 21 cameras operating at 250 Hz (MAC3D, Motion Analysis Corporation, California, USA). Individual marker trajectories were filtered using a bidirectional fourth-order low-pass Butterworth filter (15 Hz cutoff [148]) to remove high-frequency noise. Ten consecutive strides, recorded three minutes after the run started, were analyzed. Touch-down and toe-off windows were defined as follows: the touchdown window commenced when the anterior-posterior velocity of the heel marker transitioned from positive to negative and ended at the subsequent minimum in the vertical heel position. The toe-off window started 100 ms after the touchdown. It ended when either the vertical toe position (measured as the midpoint between the first and fifth metatarsal heads) exceeded 0.1 m or reached its maximum height [32, 149-151]. During these windows, touchdown onset was determined using an algorithm that identified the first peak in vertical acceleration at either the heel or the first metatarsal head marker, accommodating all foot-strike types and running shoes [150, 151]. The toe-off was identified by the time at which the peak vertical jerk (the first derivative of

acceleration) occurred for the toe (again, measured as the midpoint between the first and fifth metatarsal heads). Kinematic variables were averaged across ten steps for the right leg at each of the two running velocities. In the event of a reflective marker detachment during running, the missing marker's position was estimated using linear interpolation. Lower-limb joint angles were determined according to Figure 3-1. The foot strike angle on the sagittal plane was derived from the initial joint angle at the onset of the stride (touchdown) on the sagittal plane. KE/KF ROM was calculated as the difference between the maximum and minimum knee joint angles during strides. In addition, the average angular velocity of KE/KF during the stance phase at 11 km/h and 80% of $v\dot{V}O_{2max}$ was calculated.

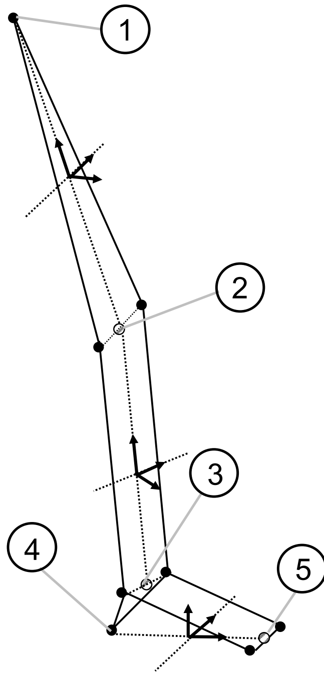


Figure 3-1. A stick figure illustrating the measurements of lower-limb joint angles. The thigh segment was defined by three axes: **x-axis:** The line between (①) the greater trochanter and (②) the midpoint between the medial tibial condyle and the fibular head. **y-axis:** Parallel to the line between the medial tibial condyle and the fibular head. **z-axis:** Perpendicular to both the x- and y-axes. The shank segment was determined by three axes: **x-axis:** The line between (②) the midpoint of the lateral tibial condyle and the distal femoral head to (③) the midpoint between the lateral and medial malleolus. **y-axis:** Parallel to the line between the lateral and medial malleolus. **z-axis:** Perpendicular to both the x- and y-axes. The foot segment was defined by three axes: **x-axis:** The line between (④) the heel and (⑤) the midpoint between the 1st and 5th metatarsal heads. **y-axis:** Parallel to the line between the 1st and 5th metatarsal heads. **z-axis:** Perpendicular to both the x- and y-axes.

3-2-3. Statistical analysis

Statistical analyses were conducted using RStudio (version 2022.07.1+554, Boston, MA). Foot strike angle on the sagittal plane and KE/KF ROM were standardized into *Z*-scores. The k-means clustering method was applied at each running velocity, based on two kinematic variables: foot strike angle in the sagittal plane and KE/KF ROM. The number of clusters was determined using the Elbow method. A linear function line was plotted between cluster numbers 1 and 10, with perpendicular lines drawn from this line to each point (Figure 3-2 [152]). The number of clusters was selected as the one that showed the longest perpendicular lines. After that, some outliers in the clusters (n = 5 at 11 km/h and n = 4 at 80% of $v\dot{V}O_{2max}$) were removed using the Distance Based Algorithm [153]. Participant characteristics and spatiotemporal variables were compared across clusters using ANOVA. Post-hoc pairwise comparisons were conducted using the Holm-Sidak procedure to identify group differences when a significant group effect ($P < 0.05$) was observed in the ANOVA. The normality of distribution was assessed using Shapiro-Wilk test, and several variables in clusters were not confirmed. Thus, Spearman rank correlation analysis was performed for all variables within each cluster to evaluate relationships between muscle functions (KE/KF torques and jump performances) and running performance-related variables (energy cost of running and WA score). The correlation coefficients were interpreted as weak ($0.0 < | r | < 0.25$), fair ($0.25 \leq | r | < 0.50$), moderate $0.50 \leq | r | < 0.75$), or strong ($0.75 \leq | r | < 1.00$) [154]. To examine whether the relationships were strengthened in the clustered compared to the non-clustered samples (i.e., within each cluster vs. the whole cohort), correlation coefficients were compared using William's test [155]. In addition, stepwise regression analysis was performed, using muscle functions with a moderate or strong relationship with either the energy cost of running or the WA score as independent variables, and both the energy cost of running and the WA score as dependent variables [156].

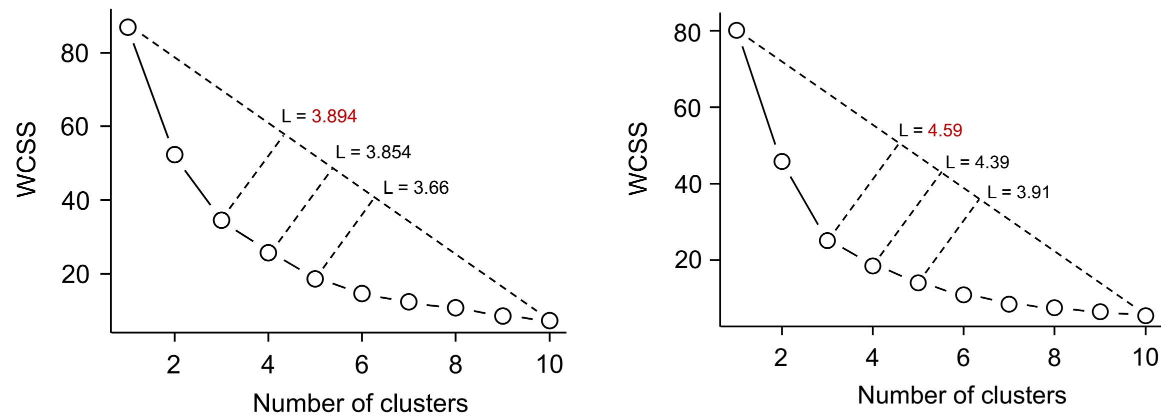


Figure 3-2. Elbow analysis for determining the optimal number of clusters. The graph shows the within-cluster sum of squares (WCSS) for cluster numbers 1, 3–5, and 10. "L" represents the length of the perpendicular lines, which indicate the optimal number of clusters based on the longest line.

Chapter 3

3-3. Results

3-3-1. Clustering for running at 11km/h

The participants were divided into three clusters in the 11km/h condition (Figure 3-3). In all (non-clustered) runners, a weak to fair relationship was observed between muscle functions (KE/KF torque and jump performance) and running performance-related variables ($|r| = 0.012$ to 0.342; see the rightmost column "ALL" in Table 3-2 for details). On the other hand, classifying runners based on running kinematics significantly strengthened these relationships in a cluster-specific manner ($|r| = 0.518$ to 0.633; see below and each column of "Clusters 1–3" in Table 3-2 for details).

Table 3-2. Correlations between muscle functions and both energy cost of running and WA score in each cluster and all runners at 11 km/h.

	Cluster 1×	Cluster 2 ○	Cluster 3 ▲	ALL
Characteristics	Dorsiflexed landing	Small KE/KF ROM	Plantarflexed landing	-
The relationship with the energy cost of running				
Isokinetic slow KE	*r* = 0.005 (-0.547 to 0.554)	*r* = 0.067 (-0.365 to 0.475)	*r* = -0.283 (-0.662 to 0.212)	*r* = -0.045 (-0.298 to 0.214)
Isokinetic fast KE	*r* = -0.189 (-0.670 to 0.404)	*r* = 0.245 (-0.197 to 0.604)	*r* = -0.290 (-0.667 to 0.205)	*r* = -0.012 (-0.267 to 0.245)
Isokinetic slow KF	*r* = 0.086 (-0.488 to 0.608)	***r* = -0.633# (-0.948 to -0.319)**	*r* = -0.115 (-0.552 to 0.372)	***r* = -0.330# (-0.540 to -0.081)**
Isokinetic fast KF	*r* = -0.180 (-0.665 to 0.412)	*r* = -0.334 (-0.662 to 0.102)	*r* = -0.221 (-0.624 to 0.274)	*r* = -0.185 (-0.421 to 0.075)
CMJ height	*r* = -0.030 (-0.572 to 0.530)	*r* = -0.164 (-0.548 to 0.277)	*r* = -0.148 (-0.575 to 0.343)	*r* = -0.113 (-0.359 to 0.147)
DJ height	*r* = -0.300 (-0.730 to 0.301)	*r* = -0.186 (-0.563 to 0.256)	***r* = -0.534# (-0.801 to -0.089)**	***r* = -0.342# (-0.550 to -0.094)**
DJ index	*r* = -0.060 (-0.591 to 0.508)	*r* = -0.251 (-0.608 to 0.191)	***r* = -0.518# (-0.793 to -0.067)**	***r* = -0.289# (-0.508 to -0.036)**
RJ height	*r* = -0.178 (-0.664 to 0.414)	*r* = -0.211 (-0.588 to 0.221)	***r* = -0.546# (-0.807 to -0.106)**	*r* = -0.250 (-0.476 to 0.006)
RJ index	*r* = -0.209 (-0.682 to 0.386)	*r* = -0.177 (-0.557 to 0.264)	***r* = -0.553# (-0.811 to -0.116)**	*r* = -0.164 (-0.403 to 0.396)
The relationship with WA score				
Isokinetic slow KE	*r* = 0.077 (-0.495 to 0.602)	*r* = -0.176 (-0.556 to 0.265)	*r* = -0.129 (-0.562 to 0.360)	*r* = -0.061 (-0.312 to 0.198)
Isokinetic fast KE	*r* = 0.095 (-0.481 to 0.614)	*r* = 0.048 (-0.381 to 0.460)	*r* = -0.139 (-0.569 to 0.351)	*r* = 0.053 (-0.206 to 0.305)
Isokinetic slow KF	*r* = 0.217 (-0.379 to 0.686)	*r* = -0.243 (-0.603 to 0.199)	*r* = -0.032 (-0.492 to 0.441)	*r* = -0.065 (-0.316 to 0.194)
Isokinetic fast KF	*r* = -0.270 (-0.715 to 0.330)	*r* = 0.154 (-0.286 to 0.541)	*r* = -0.280 (-0.661 to 0.215)	*r* = -0.185 (-0.421 to 0.075)
CMJ height	*r* = 0.153 (-0.435 to 0.649)	*r* = 0.130 (-0.309 to 0.523)	*r* = 0.031 (-0.442 to 0.491)	*r* = 0.082 (-0.178 to 0.331)
DJ height	*r* = -0.113 (-0.625 to 0.467)	*r* = 0.076 (-0.357 to 0.482)	*r* = -0.213 (-0.618 to 0.282)	*r* = -0.027 (-0.281 to 0.231)
DJ index	*r* = -0.018 (-0.563 to 0.538)	*r* = 0.054 (-0.376 to 0.465)	*r* = -0.137 (-0.568 to 0.352)	*r* = -0.001 (-0.257 to 0.255)
RJ height	*r* = -0.005 (-0.554 to 0.547)	*r* = 0.098 (-0.338 to 0.499)	*r* = -0.247 (-0.640 to 0.249)	*r* = -0.008 (-0.264 to 0.249)
RJ index	*r* = 0.074 (-0.497 to 0.601)	*r* = 0.057 (-0.374 to 0.467)	*r* = -0.266 (-0.652 to 0.229)	*r* = -0.022 (-0.277 to 0.235)

Data are presented as a correlation coefficient (95% CI).

Significant relationship with the energy cost or WA score ($P < 0.05$).

* Significant difference in the correlation coefficient of ALL runners ($P < 0.05$).

Abbreviations: KE, knee extension torque; KF, knee flexion torque; KE/KF ROM, knee extension/flexion range of motion; CMJ, counter-movement jump; DJ, drop jump; RJ, rebound jump; WA, World Athletics.

Cluster 1: Dorsiflexed landing. Only weak to fair relationships were observed between muscle functions and the energy cost of running or WA score (| *r* | = 0.005 to 0.300; Table 3-2).

Cluster 2: Small KE/KF ROM. A significant relationship was observed between slow KF torque and the energy cost of running (*r* = -0.633 [-0.948 to -0.319]; Figure 3-3). In addition, slow KF torque significantly explained the variation in the energy cost of running (Adjusted R^2 = 0.371, *P* = 0.002; Table 3-3).

Cluster 3: Plantarflexed landing. Drop and rebound jump heights and indices were significantly associated with the energy cost of running (*r* = -0.553 [-0.811 to -0.116] to -0.518 [-0.793 to -0.067]; Figure 3-3). The rebound jump index was selected as an explanatory factor for explaining the variation in the energy cost of running (Adjusted R^2 = 0.263, *P* = 0.017; Table 3-3).

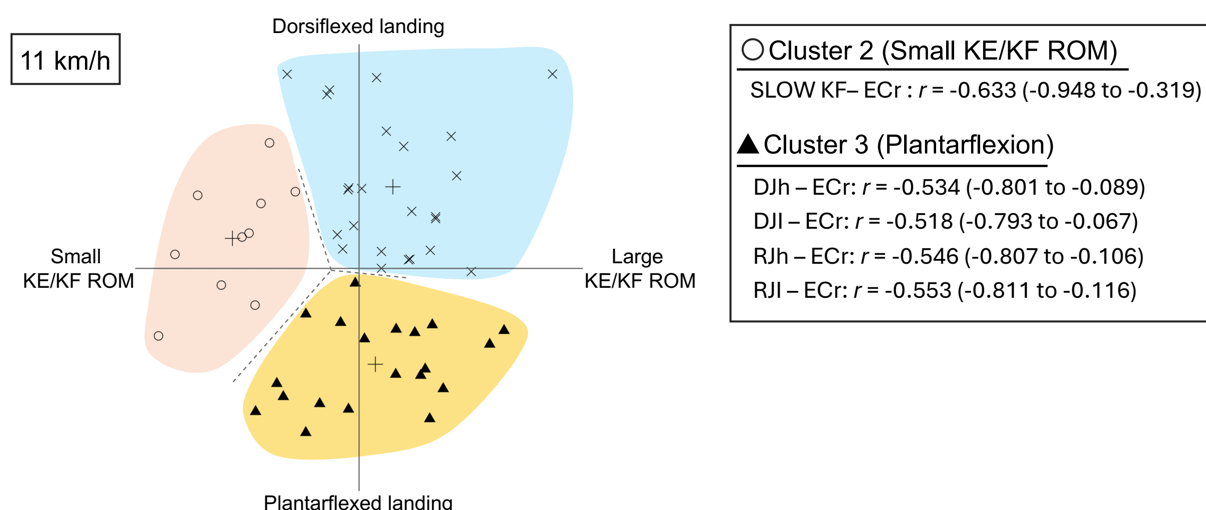


Figure 3-3. Factors associated with the energy cost of running and/or WA score when runners are classified based on running kinematics at 11 km/h. Foot strike angle and KE/KF ROM during the stance phase were converted into a *Z*-score. Significant relationships are highlighted within the right rectangles. The values in the rectangle represent a correlation coefficient between muscle functions and either the energy cost of running or performance, and its 95% CIs.

Abbreviations: KE/KF ROM, knee extension/flexion range of motion; SLOW, slow isokinetic (30°/s); KF, knee flexion torque; DJh, drop jump height; DJI, drop jump index; RJh, rebound jump height; RJI, rebound jump index; ECr, energy cost of running.

Table 3-3. Regression models for explaining energy cost of running and WA score in each cluster based on running kinematics at 11 km/h and 80% $v\dot{V}O_{2max}$.

	Equations	Adjusted R^2	P value
11 km/h			
Cluster 2	ECr ~ SLOW KF (–)	0.371	0.002
Cluster 3	ECr ~ RJI (–)	0.263	0.017
80% of $v\dot{V}O_{2max}$			
Cluster 2	WA score ~ SLOW KF (–)	0.211	0.036
Cluster 3	ECr ~ RJI (–)	0.344	0.016

(+) represents a positive relationship with a dependent variable, while (–) indicates a negative relationship with a dependent variable. For example, *ECr ~ SLOW KF* represents the negative relationship between the energy cost of running and slow isokinetic knee flexion torque.

Abbreviations: ECr, energy cost of running; WA, World Athletics; SLOW, slow isokinetic; KF, knee flexion torque; RJI, rebound jump index.

3-3-2. Clustering for running at 80% $v\dot{V}O_{2max}$

The participants were divided into three clusters in the 80% $v\dot{V}O_{2max}$ condition (Figure 3-4). In all (non-clustered) runners, a weak to fair relationship was also found between muscle functions (KE/KF torque and jump performance) and running performance-related variables ($| r |$ = 0.0004 to 0.258; see the rightmost column “ALL” in Table 3-4 for details). In contrast, classifying runners based on running kinematics significantly strengthened these relationships in a cluster-specific manner ($| r |$ = 0.510 to 0.628; see below and each column of “Clusters 1–3” in Table 3-4 for details).

Table 3-4. Correlations between muscle functions and both energy cost of running and WA score in each cluster and all runners at 80% $v\dot{V}O_{2max}$.

	Cluster 1×	Cluster 2 ○	Cluster 3 ▲	ALL
Characteristics	Dorsiflexed landing & large KE/KF ROM	Dorsiflexed landing & small KE/KF ROM	Plantarflexed landing	-
The relationship with the energy cost of running				
Isokinetic slow KE	*r* = 0.082 (-0.342 to 0.478)	*r* = 0.001 (-0.480 to 0.481)	*r* = -0.210 (-0.662 to 0.212)	*r* = 0.101 (-0.397 to 0.212)
Isokinetic fast KE	*r* = -0.004 (-0.416 to 0.409)	*r* = 0.390 (-0.112 to 0.733)	*r* = -0.001 (-0.531 to 0.530)	*r* = 0.072 (-0.188 to 0.322)
Isokinetic slow KF	***r* = 0.341*** **(-0.083 to 0.660)**	*r* = -0.159 (-0.832 to -0.288)	*r* = -0.064 (-0.552 to 0.372)	*r* = -0.297 (-0.514 to -0.044)
Isokinetic fast KF	*r* = 0.012 (-0.402 to 0.422)	*r* = 0.217 (-0.294 to 0.632)	*r* = -0.262 (-0.696 to 0.312)	*r* = -0.0004 (-0.256 to 0.256)
CMJ height	*r* = 0.257 (-0.174 to 0.605)	*r* = 0.189 (-0.321 to 0.614)	*r* = -0.332 (-0.733 to 0.241)	*r* = 0.007 (-0.250 to 0.263)
DJ height	*r* = -0.145 (-0.526 to 0.284)	*r* = -0.077 (-0.538 to 0.419)	***r* = -0.578#** **(-0.848 to -0.068)**	***r* = -0.258#** **(-0.482 to -0.002)**
DJ index	*r* = 0.092 (-0.333 to 0.486)	*r* = 0.068 (-0.427 to 0.531)	*r* = -0.458 (-0.795 to 0.096)	*r* = -0.101 (-0.348 to 0.159)
RJ height	*r* = 0.101 (-0.325 to 0.493)	*r* = -0.032 (-0.505 to 0.456)	***r* = -0.600#** **(-0.858 to -0.102)**	*r* = -0.162 (-0.401 to 0.098)
RJ index	*r* = 0.245 (-0.186 to 0.597)	*r* = 0.152 (-0.355 to 0.590)	***r* = -0.628#*** **(-0.869 to -0.146)**	*r* = -0.021 (-0.276 to 0.236)
The relationship with WA score				
Isokinetic slow KE	*r* = 0.330 (-0.095 to 0.653)	*r* = -0.049 (-0.517 to 0.442)	*r* = -0.135 (-0.621 to 0.426)	*r* = -0.061 (-0.312 to 0.198)
Isokinetic fast KE	*r* = 0.208 (-0.223 to 0.571)	*r* = -0.232 (-0.641 to 0.280)	*r* = 0.163 (-0.402 to 0.638)	*r* = 0.053 (-0.206 to 0.305)
Isokinetic slow KF	*r* = 0.200 (-0.231 to 0.566)	***r* = -0.510#** **(-0.796 to -0.039)**	*r* = -0.165 (-0.640 to 0.401)	*r* = -0.065 (-0.316 to 0.194)
Isokinetic fast KF	*r* = -0.242 (-0.595 to 0.189)	*r* = -0.349 (-0.710 to 0.158)	*r* = -0.024 (-0.548 to 0.513)	*r* = -0.185 (-0.421 to 0.075)
CMJ height	*r* = 0.027 (-0.390 to 0.434)	*r* = 0.137 (-0.368 to 0.579)	*r* = 0.142 (-0.420 to 0.625)	*r* = 0.082 (-0.178 to 0.331)
DJ height	*r* = 0.234 (-0.197 to 0.589)	*r* = -0.050 (-0.518 to 0.441)	*r* = -0.148 (-0.629 to 0.415)	*r* = -0.027 (-0.281 to 0.231)
DJ index	*r* = 0.196 (-0.235 to 0.563)	*r* = -0.102 (-0.555 to 0.398)	*r* = -0.290 (-0.711 to 0.284)	*r* = -0.001 (-0.257 to 0.255)
RJ height	*r* = 0.341 (-0.083 to 0.660)	*r* = -0.241 (-0.647 to 0.271)	*r* = 0.136 (-0.425 to 0.622)	*r* = -0.008 (-0.264 to 0.249)
RJ index	*r* = 0.201 (-0.230 to 0.566)	*r* = -0.137 (-0.579 to 0.368)	*r* = 0.056 (-0.489 to 0.570)	*r* = -0.022 (-0.277 to 0.235)

Data are presented as a correlation coefficient (95% CI).

Significant relationship with the energy cost or WA score ($P < 0.05$).

* Significant difference in the correlation coefficient of ALL runners ($P < 0.05$).

Abbreviations: KE, knee extension torque; KF, knee flexion torque; KE/KF ROM, knee extension/flexion range of motion; CMJ, counter-movement jump; DJ, drop jump; RJ, rebound jump; WA, World Athletics.

Cluster 1: Dorsiflexed landing & large KE/KF ROM. No significant relationship between muscle functions and energy cost of running or WA score (| *r* | = 0.004 to 0.341).

Cluster 2: Dorsiflexed landing & small KE/KF ROM. Only slow KF torque was significantly correlated with WA score (*r* = -0.510 [-0.796 to -0.039]; Figure 3-4), but not with the energy cost of running. The slow KF torque was selected as an explanatory factor for explaining the variation in WA score (Adjusted R^2 = 0.211, *P* = 0.036; Table 3-3).

Cluster 3: Plantarflexed landing. Significant relationships were found between both drop jump height, rebound height, and energy cost of running (*r* = -0.628 [-0.869 to -0.146] to -0.578 [-0.848 to -0.068]; Figure 3-4). In addition, the relationship between rebound jump index and energy cost of running in this cluster was significantly different from that of the whole runners (*r* = -0.628 [-0.869 to -0.146] vs. *r* = -0.021 [-0.276 to 0.236]). The regression analysis showed that the rebound jump index significantly explained variation in the energy cost of running (Adjusted R^2 = 0.344, *P* = 0.016; Table 3-3).

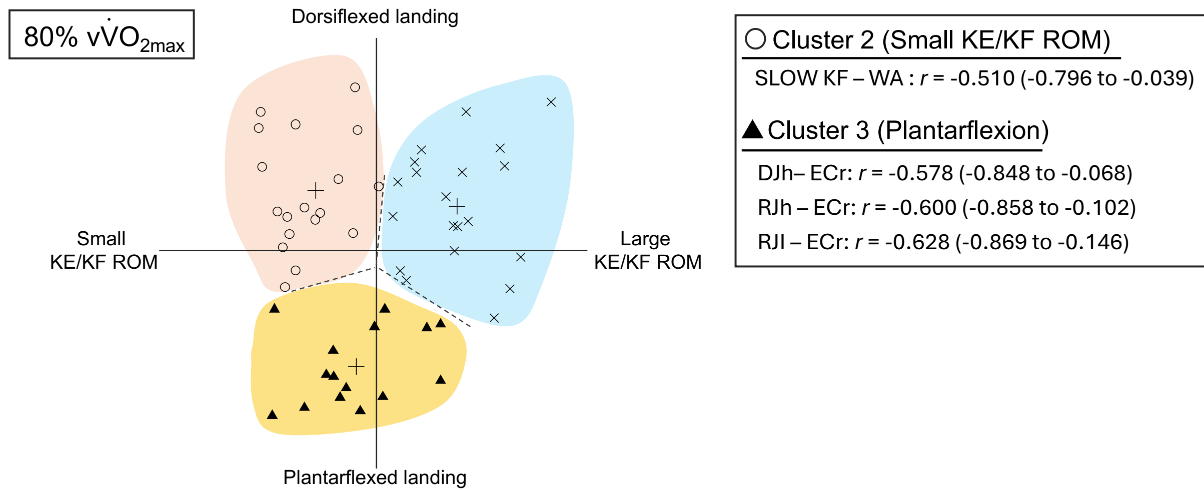


Figure 3-4. Factors associated with energy cost of running and WA score when runners are classified based on running kinematics at 80% of v$\dot{V}O_{2max}$. Foot strike angle and KE/KF ROM during the stance phase were converted into a *Z*-score. Significant relationships are highlighted within the right rectangles. The values in the rectangle represent a correlation coefficient between muscle functions and either the energy cost of running or performance, and its 95% CIs.

Abbreviations: KE/KF ROM, knee extension/flexion range of motion; SLOW, slow isokinetic (30°/s); KF, knee flexion torque; DJh, drop jump height; RJh, rebound jump height; RJI, rebound jump index; ECr, energy cost of running.

3-4. Discussion

The analyses for the whole cohort of runners showed a weak to fair correlation between muscle function and running economy or performance at both 11 km/h and 80% of $v\dot{V}O_{2max}$ (Tables 3-2 & 3- 4). The corresponding relationships were significantly strengthened in each cluster based on running kinematics, compared with the whole cohort of runners, in a cluster-specific manner (i.e., the relationship differed among the clusters), without the influence of set running velocities. This result broadly supports our hypothesis. Collectively, among master endurance runners, the contribution of muscle function to superior running economy and performance may differ with running kinematic profiles.

As expected, jump performance was related to running economy and performance in the plantarflexed-landing clusters. This result is reasonable because forefoot strikers are known to proactively utilize the SSC ability during running [41]. In contrast, slow KF torque was unexpectedly associated with running economy or performance in the cluster with a small KE/KF ROM at 11 km/h. Although limited, a previous study has suggested that leg stiffness during running is positively associated with the gastrocnemius lateralis activation (which acts as both an ankle plantarflexor and a knee flexor) while vastus lateralis activation (which acts as a knee extensor) during the propulsion phase was negatively correlated with ankle joint quasi-stiffness [157]. In addition, runners typically experience an external knee flexion moment at foot-strike, requiring them to produce substantial eccentric knee extensor torque to maintain a high leg stiffness [158]. Considering these findings, KF torque rather than jump performance may play a more critical role in preserving leg stiffness and thereby supporting running economy and performance in master endurance runners with a small KE/KF ROM.

At 11 km/h, the expected results were obtained (see the hypothetical model in Figure 1-5 in Chapter 1). Importantly, the same pattern was also confirmed at relative running velocities (14.1 ± 1.3 km/h), despite prior hypotheses being developed mainly from studies that used the same absolute running

velocity across runners [39-41, 113, 159]. This convergence across absolute and relative velocities suggests that the proposed relationships are robust to differences in velocity prescription. Increasing running velocity can shift the relative contributions of muscle groups, for example, reduced quadriceps femoris contribution to net vertical ground reaction force and greater hamstrings involvement in propulsion at higher velocities [105]. Nevertheless, the key relationships remained clear under both absolute and relative velocity conditions. Future work should further clarify whether specific kinematic or neuromuscular determinants are invariant across absolute and relative speed conditions.

This study has two limitations. Firstly, the clusters were determined by the relative positions of the recruited participants in the present study (the simulation analysis was performed in Appendix C). While the present study recruited 59 Japanese endurance runners, its findings may not be generalizable to participants of different ages, races, or competition levels. Nonetheless, the process adopted in the present study should help explore an essential factor in achieving better running economy and performance. Furthermore, pooling data in the future will enable the proposal of individualized training methods to improve running economy and performance based on runners' characteristics (e.g., race, sex, and competition levels). Secondly, the present study adopted a cross-sectional design and identified relationships between muscle function and either running economy or performance within each cluster. Thus, it remains unclear whether running economy and performance can be improved by training-induced enhancements in muscle function, which were identified as a factor associated with running economy and performance from cluster analysis in this study. Further studies are needed to clarify this point by employing a longitudinal design.

3-5. Summary

Dividing master endurance runners into clusters based on foot strike angle on the sagittal plane and KE/KF ROM significantly strengthened the relationships between muscle functions (muscle strength and jump performance) and both running economy and performance, compared with the whole non-clustered cohort. These findings suggest that the primary muscle groups responsible for propulsion and shock absorption are shaped by running kinematics regardless of running velocity in master endurance runners. For this age group, therefore, the application of clustering methods based on running kinematics provides a valuable approach for individually prescribing strength training to enhance running economy and performance.

Chapter 4. Exploring Factors Affecting the Effectiveness of Plyometric Training for Improving Running Economy in Master Endurance Runners

4-1. Rationale and aims

In this chapter, plyometric training is explored as a practical approach to improving running economy by enhancing SSC function, extending insights from Chapters 2 and 3. Building on Chapter 2, plyometric training sessions can be shorter, impose lower perceived exertion, and require no specialized equipment, yet yield comparable (or more beneficial) effects on running economy and performance compared with resistance training in master endurance runners. Chapter 3 further indicated that relationships between propulsion/shock-absorption demands and running performance become clearer when individual running kinematics (foot-strike angle and KE/KF ROM) are considered. Taken together, these observations suggest that prescribing adjunct training with the runner's kinematic profile in mind is a promising route to improving running economy and performance.

Accordingly, this chapter had two primary aims. The first was to compare the magnitude of improvements in running economy across the kinematic clusters defined in Chapter 3. The second was to examine whether the factors associated with improvements in running economy differed across the kinematic clusters. Although the analyses in this chapter focus exclusively on running economy, it is essential to note that Chapter 2 demonstrated a significant association between changes in running economy and performance. Therefore, the improvements in running economy observed here are likely to reflect concurrent improvements in running performance. It was hypothesized that runners characterized by a plantarflexed foot-strike pattern would exhibit greater improvements in running economy following plyometric training, and that within this cluster, changes in reactive jump performance would be positively associated with changes in running economy.

Chapter 4

4-2. Methods

4-2-1. Participants

Forty out of fifty-nine (participants in Chapter 3) endurance male runners (42.1 ± 5.0 years old) voluntarily participated in this study. Participants were required to meet the following inclusion criteria: (1) age of 30–50 year-old, (2) a seasonal record in a 5 km or longer race with WA points of > 54 (e.g., full-marathon record < 4:00:05) [142], (3) free from moderate injuries in the three months and minor injuries in the month preceding the study, and (4) consistent running of ≥ two days per week over the previous three months. This study was approved by the ethics committee of Ritsumeikan University (BKC-LSMH-2023-118), and all procedures used in this study were conducted in accordance with the Declaration of Helsinki. Before the experiments, all participants were fully informed of the purpose and risks of the experiment and provided written consent.

4-2-2. Study design

All participants performed plyometric training twice weekly on non-consecutive days for 10 weeks. The 10-week intervention period was based on recent review recommendations for improving running economy [92, 121]. Participants completed four experimental sessions, twice before and twice after the interventions, scheduled 24–168 hours apart. The post-training tests were conducted within one week following the final training session. All tests were performed in a climate-controlled laboratory at 22℃ (21.4–22.6℃). Before each test, participants abstained from strenuous exercise and alcohol for 24 hours and from caffeine for six hours.

In the first session, body composition, muscle strength, jump performance, and $\dot{V}O_{2max}$ were assessed. In the second session, body composition, running kinematics, and energy cost of running (running economy) were measured. Seasonal performance records were obtained from official race results

(full-marathon time, 3:04:22 ± 24:44). Body composition was assessed in both sessions and used to scale $\dot{V}O_{2max}$ and the energy cost of running. Five runners dropped out of the training intervention (n = 3 due to injuries sustained during habitual running; n = 1 due to job transfer; n = 1 due to a decline in physical condition), leaving 35 runners who completed the study. To evaluate test-retest repeatability, a subset of 21 runners (age, 39.1 ± 6.3 years; full-marathon time, 3:05:06 ± 24:48) underwent the same measurement protocol (excluding ankle-joint isometric torque) on two occasions separated by ≥ 3 months before participating in the training intervention.

4-2-3. Measurements

Body composition. Height and body mass were measured using a stadiometer-equipped scale (WB-510, TANITA Corp., Tokyo, Japan). Body fat percentage, muscle mass, and fat-free mass were assessed using a bioelectrical impedance analyzer (InBody770, InBody Japan Co., Ltd., Tokyo, Japan).

Muscle strength. Isokinetic KE /KF concentric torque and isometric ankle dorsiflexion (DF)/plantarflexion (PF) torque were assessed on the right leg in a seated position (hip angle at 90°) using a dynamometer (Biodex System IV, Biodex Medical Systems, Shirley, NY). Participants were instructed to sit deeply in the seat, place their hands on the handrail, and secure their upper body with a belt to prevent extraneous movement.

For KE and KF torque assessment, the seat was adjusted to align the lateral tibial condyle with the rotation center of the attachment. The participants first performed a warm-up consisting of isometric KE/KF at 90° of the knee joint angle with three repetitions at 50%, 70%, and 90% of their maximal effort. Then, they practiced two isokinetic concentric contractions in each of slow (30°/s) and fast (180°/s) conditions in 2–3 round trips from 90° to 0° (full extension) of the knee joint angle at 50% of their

maximal effort. Finally, maximal isokinetic KE/KF concentric torque was measured in two round trips at each isokinetic velocity with a rest period of 60 seconds. The best trial for each KE and KF torque in the ROM was selected for data analysis.

For DF and PF torque assessment, the seat was adjusted to align the lateral malleolus with the rotation center of the attachment. Isometric testing was selected because isokinetic testing at the ankle joint proved technically challenging in a pilot study, and several previous studies have validated the use of isometric DF and PF torque measurements to evaluate training effects [35, 65, 160]. The participants remained seated with the knee fully extended. The ankle joint was fixed at 90° for measurements [161, 162]. After a warm-up consisting of three isometric contractions at 50%, 70%, and 90% of maximal effort, participants performed 3 seconds of maximal voluntary isometric contraction for both DF and PF, with a 30-second rest between trials. The peak torque from each movement was selected for analysis.

Jump performance. Participants performed the CMJ, 30 cm drop jump, and three rebound jumps, each conducted three times. For the CMJ test, participants performed a rapid downward squat followed by a vertical jump with an arm swing. Jump height was recorded using an optical measurement system (OptoJump Next, Microgate, Bolzano, Italy). The best trial for jump height was used for data analysis. For the drop jump test, participants first stood on a 30 cm box and then stepped off the box to land and rebound jump with an arm swing for maximum height with minimal ground contact time. For the three rebound jumps, participants performed three consecutive vertical jumps with the same goals as the drop jump. The optical measurement system measured jump height, contact time, and drop/rebound jump index (jump height divided by contact time). The best trial for the jump index was used for data analysis. If two or more trials had identical jump indices, the trial with the highest jump height was chosen.

$\dot{V}O_{2max}$. $\dot{V}O_{2max}$ was measured using a treadmill without incline (Valiant Ultra; Lode BV, Groningen, Netherlands), a breath-by-breath gas analyzer (AE-310s, Minato Medical Science, Osaka, Japan), and a face mask (AMA104 and AMA512, Minato Medical Science, Osaka, Japan). Before the test session, the gas analyzer was calibrated with standard reference gases (16% O_2 and 5% CO_2). Heart rate was recorded using a heart rate monitor (Polar H10, Polar, Kempele, Finland). Participants completed a warm-up by running at 8 and 11 km/h for 4 minutes each, separated by a 2-minute break (1-minute walk at 3.2 km/h and 1-minute rest). After a 2-minute rest, an incremental test was conducted: treadmill velocity started at 8 km/h, increased by 1 km/h every minute up to 14 km/h, and then by 0.6 km/h each minute until volitional exhaustion. Exhaustion was defined as the participant being unable to maintain the required velocity. If this point was not reached, the following criteria were used for the attainment of $\dot{V}O_{2max}$: heart rate greater than 90% of age-predicted maximal heart rate (220 - runners' age); RER greater than 1.10 [107]; and not observing an increase of more than 1 mL/kg/min of $\dot{V}O_2$ at a stage [143]. $\dot{V}O_{2max}$ was determined as the highest $\dot{V}O_2$ value using a 30-second moving window. If participants did not complete the entire final stage (i.e., < 1 minute), $v\dot{V}O_{2max}$ was calculated based on the fraction of the stage completed. For instance, if a participant completed only 30 seconds at 13 km/h (with a 1 km/h increment rate), the $v\dot{V}O_{2max}$ was calculated as 13.5 km/h (13 + 1 × 30/60) [67].

Energy cost of running. In the second session, the energy cost of running was measured using a 0%-gradient treadmill (Integrity SL Console; Life Fitness, Illinois, USA) with the same gas analyzer and mask as for the $\dot{V}O_{2max}$ measurement. The participants ran at 8 km/h and 11 km/h for 4 minutes each as a warm-up, then at 80% of $v\dot{V}O_{2max}$ for 30 minutes. 80% of $v\dot{V}O_{2max}$ was adopted in this study because runners can theoretically continue running at this velocity without breaks for more than 2 hours [33] and can predict a 16 km running time [144]. Energy cost was calculated from the average $\dot{V}O_2$ and $\dot{V}CO_2$ values after the

first 5 minutes of running (5–30 minutes). Substrate utilization (g/min) was estimated using updated nonprotein respiratory quotient equations [145]. Energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 and 4.07 kcal, respectively [146]. Finally, the energy cost of running was expressed as the total energy expenditure per kilometer (kcal/km).

Running kinematics. Thirty-two reflective markers were affixed to anatomical landmarks. Motion was recorded at 250 Hz using 21 infrared cameras and Cortex software (MAC3D; Motion Analysis Corporation, CA, USA). Raw marker trajectories were low-pass filtered using a fourth-order Butterworth filter with a 15 Hz cutoff [148]. Running at 80% $v\dot{V}O_{2max}$ for 30 minutes was captured. Ten consecutive strides were analyzed during the final minute of each 5-minute interval throughout the 30-minute session, and the running kinematics were averaged across six time points (4-5, 9-10, 14-15, 19-20, 24-25, and 29-30 minutes). Touchdown and toe-off events were defined via velocity and position changes of heel and toe markers: touchdown began when the forward velocity of the heel marker turned negative and ended at the lowest vertical heel position; toe-off began 100 ms after touchdown and ended when the toe marker's height exceeded 0.1 m or reached its peak [32, 149-151]. Touchdown timing was refined using the peak in vertical acceleration, and toe-off by the peak in vertical jerk [150, 151]. Based on these data, joint kinematics on the sagittal plane (ankle, knee, hip) and spatiotemporal variables (step frequency, ground contact time, flight time, duty factor) were evaluated. The running kinematics on the sagittal plane were extracted because it was hypothesized that plyometric training would reduce the energy cost of running through enhancing the leg stiffness (the sagittal plane motion). In addition, as baseline running motion (foot-strike angle and KE/KF ROM during the stance phase) affects the effects of plyometric training on running economy, these variables were extracted. Leg stiffness during running was calculated using

method E described by Blum et al. [163], based on body mass, leg length, contact and flight times, and the leg angle of attack.

4-2-4. Intervention

Participants performed the prescribed training program in two sessions per week for 10 weeks, with at least 48 hours between sessions. Each training was performed with 30 seconds between the sets. Participants performed the training program at their preferred places and recorded videos of their sessions (Table 4-1). They were instructed to maximize jump height while minimizing ground contact time (except for CMJ and jump-rope exercises). Participants were asked to record each training session and submit it to the author. The investigators reviewed the videos to check the execution of the exercises and provided feedback when corrections were necessary. The participants were instructed to maintain regular running training but refrain from running training 6 hours before conducting the added plyometric training sessions to avoid the influence of fatigue and potential interference effects [127, 128]. Interval running training and continuous running volume were assessed in participants by reviewing their training logs during and 1 month before the intervention. Interval running training was defined as intermittent training over ≤ 1000 m; while continuous running training volume was defined as constant without rest running training on > 1000 m [42-44].

Table 4-1. Training programs in plyometric training.

	Week 1–2	Week 3–4	Week 5–6	Week 7–8	Week 9–10
BL jump rope	3 sets × 30 seconds	3 sets × 40 seconds	3 sets × 45 seconds		
Scissors jump	3 sets × 15 seconds				
BL hopping	3 sets × 15 seconds	3 sets × 18 seconds	3 sets × 20 seconds		
CMJ		3 sets × 15 seconds	3 sets × 20 seconds		
SL jump rope				3 sets × 15 seconds × 2	3 sets × 20 seconds × 2
SL hopping				3 sets × 7 seconds × 2	3 sets × 10 seconds × 2
Alternative jump				3 sets × 15 seconds × 2	3 sets × 20 seconds × 2

Abbreviations: BL, both legs; CMJ, counter-movement jump; SL, single leg.

4-2-5. Statistical analyses

All descriptive results are reported as mean ± SD; statistical significance was set at $P < 0.05$. Normality was assessed with the Shapiro-Wilk test. Clustering methods were identical to those described in Chapter 3 (n = 59). Two datasets were analyzed: a plyometric-training dataset (n = 35) and a repeatability dataset (n = 21). Analyses were performed in R (RStudio 2023.12.0+369).

Changes in variables. Pre-post changes in measured variables (excluding ankle-joint isometric torque and running volumes) were tested with a two-way repeated-measures ANOVA (Time: pre vs. post × Dataset: plyometric-training vs. repeatability). When the interaction was significant, paired *t*-tests probed within-dataset changes. In the plyometric-training dataset, a paired *t*-test also evaluated pre- and post-changes in running volume (continuous and interval training), PF, and DF torque. A paired *t*-test was also performed after clustering to test the difference in the measured variables between the pre- and post-intervention periods within each cluster. *P*-values were adjusted with the Holm-Sidak method. Effect sizes were expressed as Hedges' *g* (trivial ≤ 0.20, small 0.20–0.49, moderate 0.50–0.99, and large ≥ 1.00) [89].

To investigate differences in improvements in energy cost among clusters, runners were classified as having improved running economy at 80% $v\dot{V}O_{2max}$ if the improvement exceeded the typical error (TE = 1.45%; Appendix A). LMM (time-by-cluster) compared the magnitude of running-economy improvement across clusters, including running volume (continuous and interval running volume) as a covariate, and a chi-square test compared the proportion of "improvers" between clusters.

Relationships with the changes in the energy cost of running. The relationships between changes in muscle strength, jump performance, and spatiotemporal variables and changes in energy cost were analyzed using an LMM, with both continuous and interval running volumes included as covariates. *P*-

values were adjusted in each muscle strength (six variables), jump performance (five variables), and spaciotemporal variables (five variables) with the Holm-Sidak method. Standardized beta coefficients (SBCs) were computed to compare the relative strength of predictor variables with different units [164]. If the SBC is 0.1, it indicates that a 1 SD increase in the predictor variable is associated with a 0.1 SD increase in the outcome variable. SBCs were compared between the plyometric training and repeatability datasets based on their 95% CIs, excluding PF and DF torques. If the 95% CIs did not overlap, the SBCs were judged as significantly different between the datasets.

To investigate the relationship between changes in muscle function and changes in running economy within each cluster, LMM was performed, including running volume as a covariate, and the models were compared using the SBCs. *P*-values for muscle strength (six variables) and jump performance (five variables) were adjusted using the Holm-Sidak method.

Model for explaining the change in energy cost of running. LMM was also applied using the variables that showed significant relationships in the preceding LMM after excluding highly correlated variables to address collinearity (variance inflation factor > 2.5 [32]). The conditional R^2 was calculated to estimate the power to explain the variation in changes in the energy cost of running [165].

4-3. Results

4-3-1. The participants characteristics

Participants' characteristics of the plyometric training and repeatability datasets are summarized in Table 4-2. Main effects of group and time, and the interaction, were not observed for most variables (P = 0.102–0.845). In contrast, a significant interaction was found between body mass and body fat percentage (P =

0.001–0.005), suggesting that the changes in body mass and body fat percentage in the plyometric-training dataset (reductions of both variables) differed significantly from those in the repeatability dataset (increases in the corresponding variables). Continuous (P = 0.152) and interval running training volume (P = 0.237) were not significantly different between pre- and post-test.

Table 4-2. Pre- and post-intervention comparisons of anthropometric, physiological, and training variables in the plyometric training dataset.

	Plyometric training		Repeatability		Main effect of group	Main effect of time	Interaction
	Pre-test	Post-test	Pre-test	Post-test			
Height [m]	1.73 ± 0.06	1.73 ± 0.06	1.74 ± 0.06	1.74 ± 0.07	$P = 0.780$	$P = 0.102$	$P = 0.229$
Body mass [kg]	64.7 ± 8.0	64.1 ± 7.8	63.1 ± 8.0	64.7 ± 8.6	$P = 0.845$	$P = 0.190$	**$P = 0.005$**
Body fat percentage [%]	13.1 ± 4.0	12.0 ± 4.3	10.7 ± 4.5	12.0 ± 3.2	$P = 0.298$	$P = 0.606$	**$P = 0.001$**
Muscle mass [kg]	52.4 ± 5.8	52.8 ± 5.9	53.1 ± 6.4	53.0 ± 6.2	$P = 0.804$	$P = 0.411$	$P = 0.234$
Fat-free mass [kg]	55.7 ± 6.2	56.0 ± 6.3	56.3 ± 7.1	56.3 ± 6.6	$P = 0.825$	$P = 0.347$	$P = 0.362$
$\dot{V}O_{2max}$ [mL/kg/min]	57.5 ± 6.1	58.5 ± 6.1	57.6 ± 5.3	57.6 ± 5.7	$P = 0.790$	$P = 0.226$	$P = 0.226$
$v\dot{V}O_{2max}$ [km/h]	17.6 ± 1.4	17.7 ± 1.4	17.9 ± 1.4	18.1 ± 1.2	$P = 0.413$	$P = 0.062$	$P = 0.480$
Continuous running [km/month]	289.2 ± 107.3	311.1 ± 101.1	–	–	–	–	–
Interval running [km/month]	24.2 ± 18.3	26.2 ± 21.5	–	–	–	–	–

Mean ± SD values are shown for each variable before and after the training intervention.

4-3-2. The changes in the energy cost of running

Non-clustered runners. A significant interaction between time by group in the energy cost of running (Time: $P < 0.001$, Group: $P = 0.038$, Interaction: $P = 0.015$), indicating that the reduction of the energy cost through plyometric training was significantly greater than that observed in the repeatability dataset (Figure 4-1). Moreover, the 10-week plyometric training significantly reduced the energy cost of running at 80% of $v\dot{V}O_{2max}$ by 3.9% only in the plyometric training dataset ($P = 0.002$).

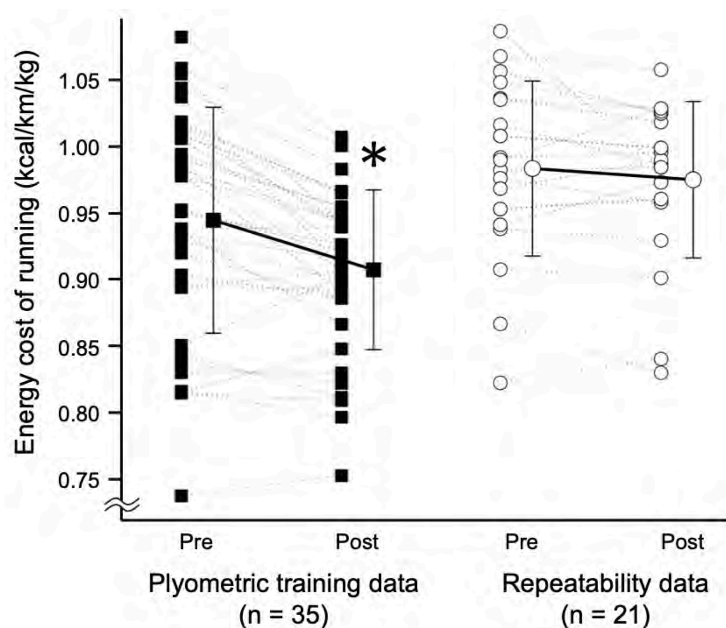


Figure 4-1. Changes in the energy cost of running in the plyometric training and repeatability datasets. Individual and group-level changes in the energy cost of running are shown for the training group (black squares) and repeatability group (white circles). Each line represents an individual participant. Thick lines and error bars indicate group means ± SDs.
* means a significant difference to pre-test in post-hoc paired *t*-test ($P < 0.05$).

Clustered runners. No significant between-cluster differences were observed in the magnitude of reduction of energy cost of running (time: $P = 0.002$; cluster: $P = 0.597$; interaction: $P = 0.676$; Figure 4-2). Likewise, the proportion of runners classified as "improved" after plyometric training did not differ across clusters ($P = 0.580$–0.900; Figure 4-2).

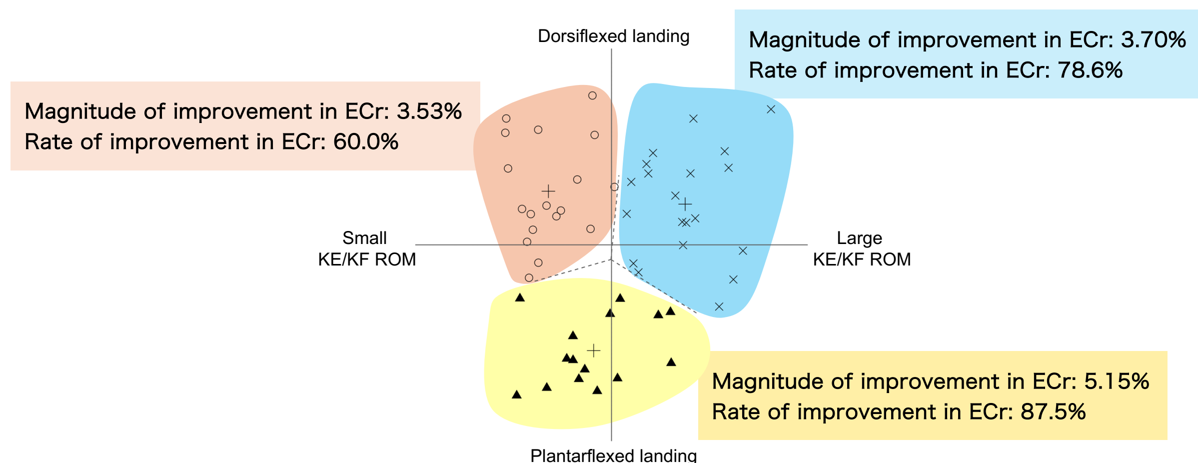


Figure 4-2. The magnitude of improvement in running economy and rate of runners who improved running economy. There was no significant difference in them among the clusters.
Abbreviations: KE/KF ROM, knee extension/flexion range of motion; ECr, energy cost of running.

4-3-3. The changes in muscle strength, jump performance, and running kinematics

Non-clustered runners. There were significant interactions in isokinetic 30°/s and 180°/s KE, CMJ height, and drop and rebound jump height and index (*P* = 0.001–0.045; Table 4-3). Post-hoc analyses revealed that 30°/s KE torque (*P* = 0.024), drop jump performance (*P* = 0.002–0.005), and rebound jump index (*P* = 0.044) performance significantly increased from pre- to post-test. In addition, significant interactions were found for ground contact time, flight time, and duty factor (*P* = 0.001–0.009). However, post-hoc analysis did not detect any significant differences in the changes in the variables from pre- to post-test between the plyometric training and repeatability data, indicating that ground contact time tends to shorten and flight time tends to lengthen after the plyometric training intervention. A paired *t*-test showed a significant increase in DF and PF torque before and after the plyometric training intervention, as compared with the repeatability data (both for *P* = 0.002).

Table 4-3. Pre- and post-intervention comparisons of muscle strength, jump performance, and spatiotemporal variables in plyometric training dataset.

	Plyometric training		Repeatability		Main effect of group	Main effect of time	Interaction
	Pre-test	Post-test	Pre-test	Post-test			
Muscle strength							
30°/s isokinetic KE [N•m/kg]	**2.42 ± 0.41**	**2.55 ± 0.35***	2.54 ± 0.39	2.49 ± 5.4	$P = 0.311$	$P = 0.671$	$\boldsymbol{P = 0.043}$
180°/s isokinetic KE [N•m/kg]	**1.54 ± 0.33**	**1.64 ± 0.30***	1.61 ± 0.26	1.61 ± 0.25	$P = 0.806$	$P = 0.452$	$\boldsymbol{P = 0.005}$
30°/s isokinetic KF [N•m/kg]	1.18 ± 0.23	1.24 ± 0.22	1.22 ± 0.21	1.22 ± 0.23	$P = 0.451$	$P = 0.053$	$P = 0.476$
180°/s isokinetic KF [N•m/kg]	0.98 ± 0.16	0.97 ± 0.14	0.93 ± 0.14	0.96 ± 0.15	$P = 0.775$	$P = 0.548$	$P = 0.379$
Isometric DF [N•m/kg]	**0.54 ± 0.08**	**0.60 ± 0.12** #	–	–	–	–	–
Isometric PF [N•m/kg]	**1.55 ± 0.44**	**1.70 ± 0.42** #	–	–	–	–	–
Jump performance							
CMJ height [cm]	35.7 ± 5.7	36.5 ± 5.2	37.3 ± 6.1	35.7 ± 5.4	$P = 0.390$	$P = 0.593$	$\boldsymbol{P = 0.005}$
Drop jump height [cm]	**29.2 ± 5.5**	**31.2 ± 5.4***	29.9 ± 5.1	28.7 ± 5.6	$P = 0.635$	$P = 0.451$	$\boldsymbol{P = 0.001}$
Drop jump index [m/s]	**1.56 ± 0.39**	**1.69 ± 0.40***	1.56 ± 0.36	1.52 ± 0.36	$P = 0.788$	$P = 0.113$	$\boldsymbol{P = 0.005}$
Rebound jump height [cm]	**28.1 ± 5.9**	**30.1 ± 5.6***	27.2 ± 6.0	27.8 ± 4.9	$P = 0.734$	$P = 0.514$	$\boldsymbol{P = 0.045}$
Rebound jump index [m/s]	**1.49 ± 0.41**	**1.60 ± 0.35***	1.46 ± 0.37	1.47 ± 0.29	$P = 0.866$	$P = 0.145$	$\boldsymbol{P = 0.010}$
Spatiotemporal variables							
Ground contact time [ms]	233.4 ± 14.5	231.3 ± 13.5	270.3 ± 12.5	270.1 ± 14.1	$P = 0.931$	$P = 0.332$	$\boldsymbol{P = 0.009}$
Flight time [ms]	101.9 ± 19.7	104.4 ± 20.1	83.8 ± 19.4	77.9 ± 19.5	$P = 0.329$	$P = 0.057$	$\boldsymbol{P = 0.001}$
Duty factor [-]	0.379 ± 0.025	0.375 ± 0.025	0.382 ± 0.022	0.389 ± 0.023	$P = 0.390$	$P = 0.593$	$\boldsymbol{P = 0.005}$
Step frequency [step/min]	179.9 ± 12.5	179.5 ± 12.3	170.0 ± 9.6	173.0 ± 10.4	$P = 0.509$	$P = 0.316$	$P = 0.206$
Leg stiffness [N•m/kg]	32.2 ± 4.0	32.8 ± 4.3	34.8 ± 5.9	34.1 ± 4.5	$P = 0.301$	$P = 0.541$	$P = 0.143$

Mean ± SD values are shown for each variable before and after the training intervention.

* means a significant difference to pre-test ($P < 0.05$) after adjusting P-values with the Holm-Sidak method.

means a significant change from pre- to post-test ($P < 0.05$) via a paired t-test.

Abbreviations: KE, knee extension; KF, knee flexion; DF, dorsiflexion; PF, plantarflexion; CMJ, counter-movement jump.

Clustered runners. Overall, pre-post changes were modest and broadly similar in direction and magnitude across clusters (Table 4-4). Cluster 1 (dorsiflexed landing and small KE/KF ROM) showed significant gains in isokinetic KE strength at 30°/s (+20.3%), PF torque (+15.9%), drop jump height (+12.4%) and index (+14.1%), and rebound jump index (+20.2%). Cluster 2 (dorsiflexed landing and large KE/KF ROM) exhibited significant improvements in isometric DF torque (+9.9%) and drop-jump index (+7.1%). Cluster 3 (plantarflexed landing) showed significant increases in PF torque (+20.1%) and drop jump index (+6.9%). For spatiotemporal variables, ground-contact time tended to shorten slightly, step rate and duty factor shifted only marginally, and flight time was unchanged across the clusters.

Table 4-4. Pre- and post-intervention comparisons of muscle strength, jump performance, and spatiotemporal variables across clusters.

	Dorsiflexed & Small KE/KF ROM (n = 9)	Dorsiflexed & Large KE/KF ROM (n = 17)	Plantarflexed landing (n = 8)
Muscle strength	Hedges' *g* (95% CIs)	Hedges' *g* (95% CIs)	Hedges' *g* (95% CIs)
30°/s isokinetic KE [N•m/kg]	**0.855 (0.079 to 1.632) ***	-0.029 (-0.505 to 0.446)	0.368 (-0.351 to 1.090)
180°/s isokinetic KE [N•m/kg]	0.662 (-0.067 to 1.390)	0.459 (-0.043 to 0.960)	0.155 (-0.543 to 0.852)
30°/s isokinetic KF [N•m/kg]	0.470 (-0.223 to 1.161)	0.204 (-0.276 to 0.685)	0.455 (-0.277 to 1.187)
180°/s isokinetic KF [N•m/kg]	0.079 (-0.575 to 0.734)	-0.087 (-0.563 to 0.389)	-0.145 (-0.708 to 0.679)
Isometric DF [N•m/kg]	0.477 (-0.217 to 1.173)	**0.542 (0.031 to 1.054) ***	0.647 (-0.124 to 1.416)
Isometric PF [N•m/kg]	**0.790 (0.030 to 1.554) ***	0.320 (-0.168 to 0.808)	**0.893 (0.057 to 1.728) ***
Jump performance	Hedges' *g* (95% CIs)	Hedges' *g* (95% CIs)	Hedges' *g* (95% CIs)
CMJ height [cm]	0.591 (-0.123 to 1.309)	0.193 (-0.287 to 0.673)	0.148 (-0.550 to 0.845)
Drop jump height [cm]	**0.965 (0.158 to 1.772) ***	0.498 (-0.008 to 1.002)	0.277 (-0.431 to 0.985)
Drop jump index [m/s]	**1.130 (0.276 to 1.987) ***	**0.585 (0.069 to 1.101) ***	**0.950 (0.097 to 1.801) ***
Rebound jump height [cm]	0.497 (-0.201 to 1.188)	0.447 (-0.053 to 0.947)	0.371 (-0.349 to 1.091)
Rebound jump index [m/s]	**0.884 (0.100 to 1.667) ***	0.460 (-0.042 to 0.961)	0.189 (-0.511 to 0.889)
Spatiotemporal variables	Hedges' *g* (95% CIs)	Hedges' *g* (95% CIs)	Hedges' *g* (95% CIs)
Ground contact time [ms]	-0.396 (-1.078 to 0.285)	-0.378 (-0.871 to 0.115)	0.010 (-0.683 to 0.703)
Flight time [ms]	0.353 (-0.323to 1.028)	0.143 (-0.335 to 0.621)	0.353 (-0.323 to 1.031)
Duty factor [-]	-0.372 (-1.053 to 0.306)	-0.209 (-0.690 to 0.272)	-0.421 (-1.150 to 0.306)
Step frequency [step/min]	-0.103 (-0.758 to 0.552)	0.142 (-0.336 to 0.620)	-0.226 (-0.973 to 0.441)
Leg stiffness [N•m/kg]	-0.432 (-1.121 to 0.255)	-0.063 (-0.538 to 0.413)	0.221 (-0.481 to 0.924)

Hedges' *g* with 95% CIs and corresponding *P*-values are reported for each comparison.

* means a significant change from pre to post-test ($P < 0.05$) after adjusting *P*-values with the Holm-Sidak method.

Abbreviations: KE/KF ROM, knee extension/flexion range of motion; KE, knee extension; KF, knee flexion; DF, dorsiflexion; PF, plantarflexion; CMJ, counter-movement jump.

4-3-4. The factors associated with the change in the energy cost of running

Non-clustered runners. No significant differences in SBCs were observed between the plyometric training and the repeatability data for any of the variables (Table 4-5). In addition, a significant SBC was not found in the repeatability data (SBC = -0.189 to 0.490, *P* = 0.110–1.000). In the plyometric training dataset, the LMM revealed no significant association between changes in muscle strength and changes in the energy cost of running (SBC = -0.214 to 0.079, *P* = 0.277–1.000). In contrast, the changes of drop and rebound jump performance (height and index) were significantly correlated to the reduction of the energy cost of running (SBC = -0.569 to -0.308, $P \leq 0.035$; Figure 4-3), while no significant association was found for CMJ height (SBC = -0.056, *P* = 0.693). Step frequency change was also significantly associated with changes in energy cost (SBC = 0.490, *P* = 0.008; Figure 4-3), whereas no significant relationships were found for other spatiotemporal variables (SBC = -0.251 to 0.144, *P* = 0.330–0.835). When these variables were entered into the LMM, a significant interaction between rebound jump height and step frequency was observed. The model showed a conditional R^2 of 0.514 and was statistically significant (*P* = 0.005). Baseline running motion (foot-strike angle or KE/KF ROM during the stance phase) was not significantly associated with the percentage change in energy cost (*r* = -0.157 to 0.079, *P* = 0.367–0.650).

Table 4-5. Comparison of SBCs for variables associated with changes in the energy cost of running between plyometric training and repeatability data.

	Plyometric training data (n = 35)		Repeatability data (n = 21)	
Muscle strength	SBC [95% CIs]	*P* value of SBC	SBC [95% CIs]	*P* value of SBC
30°/s isokinetic KE	-0.112 [-0.293, 0.070]	0.676	0.290 [0.003, 0.577]	0.192
180°/s isokinetic KE	-0.167 [-0.406, 0.072]	0.667	0.203 [-0.127, 0.532]	0.654
30°/s isokinetic KF	0.015 [-0.206, 0.235]	1.000	-0.073 [-0.388, 0.241]	0.654
180°/s isokinetic KF	0.079 [-0.168, 0.326]	1.000	-0.177 [-0.492, 0.137]	0.654
Isometric DF	-0.214 [-0.452, 0.024]	0.387	–	–
Isometric PF	-0.180 [-0.356, -0.004]	0.277	–	–
Jump performance	SBC [95% CIs]	*P* value of SBC	SBC [95% CIs]	*P* value of SBC
CMJ height	-0.056 [-0.335, 0.224]	0.693	0.439 [0.067, 0.811]	0.110
Drop jump height	**-0.569 [-0.766, -0.371]**	**< 0.001**#	-0.091 [-0.426, 0.044]	1.000
Drop jump index	**-0.478 [-0.740, -0.216]**	**0.002**#	-0.097 [-0.451, 0.258]	1.000
Rebound jump height	**-0.537 [-0.776, -0.299]**	**< 0.001**#	-0.076 [-0.482, 0.330]	1.000
Rebound jump index	**-0.308 [-0.561, -0.056]**	**0.035**#	-0.008 [-0.365, 0.348]	1.000
Spatiotemporal variables	SBC [95% CIs]	*P* value of SBC	SBC [95% CIs]	*P* value of SBC
Ground contact time	-0.251 [-0.535, 0.033]	0.330	-0.189 [-0.457, 0.079]	0.644
Flight time	-0.218 [-0.497, 0.061]	0.371	0.187 [-0.048, 0.422]	0.585
Duty factor	0.144 [-0.133, 0.421]	0.605	-0.188 [-0.377, 0.002]	0.342
Step frequency	**0.490 [0.195, 0.785]**	**0.008**#	0.075 [-0.223, 0.373]	1.000
Leg stiffness	0.030 [-0.258, 0.318]	0.835	-0.081 [-0.426, 0.263]	1.000

SBCs with 95% CIs are shown for each explanatory variable in both the plyometric training dataset (n = 35) and repeatability dataset (n = 21).

means a significant SBC (*P* < 0.05) after adjusting *P*-values with the Holm-Sidak method.

Abbreviations: SBC, standardized beta coefficient; KE, knee extension; KF, knee flexion; DF, dorsiflexion; PF, plantarflexion.

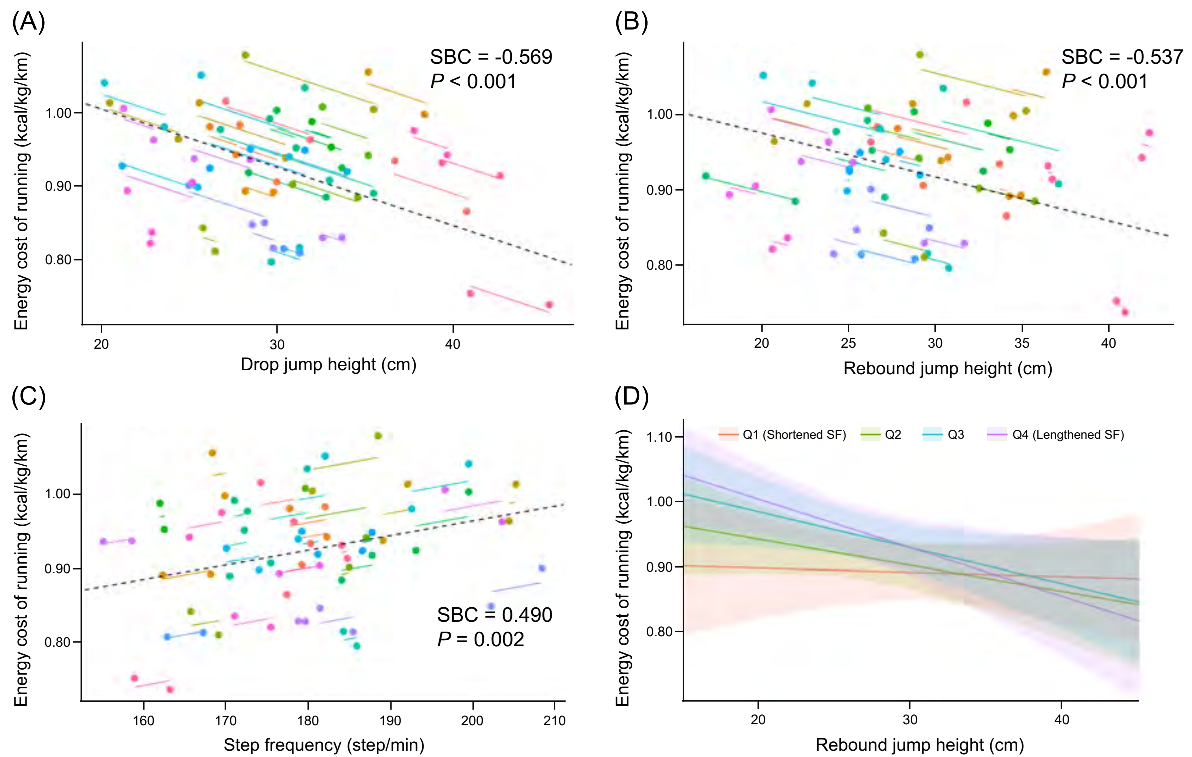


Figure 4-3. Associations between changes in the energy cost of running and (A) drop jump height, (B) rebound-jump height, (C) step frequency, and (D) the interaction between rebound-jump height and step frequency.

Colored lines represent individual participants, and dashed lines indicate the fitted regression line. Standardized beta coefficients (SBC) and corresponding *P*-values are presented for each relationship (A–C). Panel (D) illustrates the interaction effect between the changes in rebound-jump height and step frequency on the energy cost of running. For visualization, step frequency was divided into quartiles, and predicted values of the energy cost of running were plotted against rebound-jump height across each quartile group. Shaded ribbons represent 95% CIs for each prediction line.

Clustered runners. Except for cluster 1, changes in drop-jump height were significantly associated with changes in running economy (Cluster 1: SBC = -0.630, *P* = 0.038; Cluster 2: SBC = -0.544, *P* = 0.042; Cluster 3: SBC = -0.850, *P* = 0.033; Table 4-6). In addition, Clusters 2 and 3 showed a significant association between changes in drop jump index and energy cost of running (Cluster 2: SBC = -0.542, *P* = 0.043; Cluster 3: SBC = -1.053, *P* = 0.019; Figure 4-4). The conditional R^2 was 0.450 (*P* = 0.012) in Cluster 2, and 0.689 (*P* = 0.004) in Cluster 3. By contrast, no other muscle function or spaciotemporal variables exhibited significant SBCs with changes in running economy across any cluster.

Table 4-6. SBCs for variables associated with changes in the energy cost of running across clusters.

	Dorsiflexed & Small KE/KF ROM (n = 9)	Dorsiflexed & Large KE/KF ROM (n = 17)	Plantarflexed landing (n = 8)
Muscle strength	SBC [95% CIs]	SBC [95% CIs]	SBC [95% CIs]
30°/s isokinetic KE	0.070 [-0.821, 0.962]	-0.105 [-0.652, 0.442]	-0.189 [-1.171, 0.792]
180°/s isokinetic KE	-0.003 [-0.897, 0.891]	-0.260 [-0.791, 0.272]	0.218 [-0.757, 1.194]
30°/s isokinetic KF	0.052 [-0.840, 0.945]	0.236 [-0.299, 0.771]	0.409 [-0.502, 1.318]
180°/s isokinetic KF	0.260 [-0.604, 1.118]	-0.283 [-0.811, 0.244]	0.072 [-0.924, 1.072]
Isometric DF	-0.268 [-1.131, 0.593]	0.129 [-0.417, 0.674]	0.140 [-0.850, 1.133]
Isometric PF	-0.270 [-1.127, 0.590]	0.118 [-0.428, 0.665]	0.257 [-0.708, 1.220]
Jump performance	SBC [95% CIs]	SBC [95% CIs]	SBC [95% CIs]
CMJ height	0.325 [-0.521, 1.170]	-0.010 [-0.647, 0.448]	0.215 [-0.761, 1.191]
Drop jump height	-0.630 [-1.321, 0.064]	**-0.544 [-0.911, -0.176]** [#]	**-0.850 [-1.654, -0.184]** [#]
Drop jump index	-0.215 [-1.090, 0.658]	**-0.542 [-1.00, -0.080]** [#]	**-1.053 [-1.570, -0.532]** [#]
Rebound jump height	-0.287 [-1.136, 0.569]	-0.260 [-0.792, 0.271]	-0.564 [-1.388, 0.261]
Rebound jump index	-0.101 [-0.990, 0.789]	0.009 [-0.542, 0.559]	-0.565 [-1.392, 0.259]
Spatiotemporal variables	SBC [95% CIs]	SBC [95% CIs]	SBC [95% CIs]
Ground contact time	-0.456 [-1.252, 0.340]	-0.418 [-0.918, 0.082]	-0.448 [-1.341, 0.444]
Flight time	0.090 [-0.800, 0.980]	0.112 [-0.435, 0.658]	-0.085 [-1.081, 0.910]
Duty factor	-0.145 [-1.029, 0.739]	-0.187 [-0.727, 0.354]	0.025 [-0.973, 1.016]
Step frequency	0.498 [-0.276, 1.268]	0.221 [-0.316, 0.758]	0.467 [-0.416, 1.347]
Leg stiffness	-0.194 [-1.073, 0.683]	-0.069 [-0.618, 0.481]	-0.018 [-1.015, 0.981]

SBCs with 95% CIs are shown for each explanatory variable in each cluster.

[#] means a significant SBC ($P < 0.05$) after adjusting P-values with the Holm-Sidak method.

Abbreviations: KE/KF ROM, knee extension/flexion range of motion; SBC, standardized beta coefficient; KE, knee extension; KF, knee flexion; DF, dorsiflexion; PF, plantarflexion; CMJ, counter-movement jump.

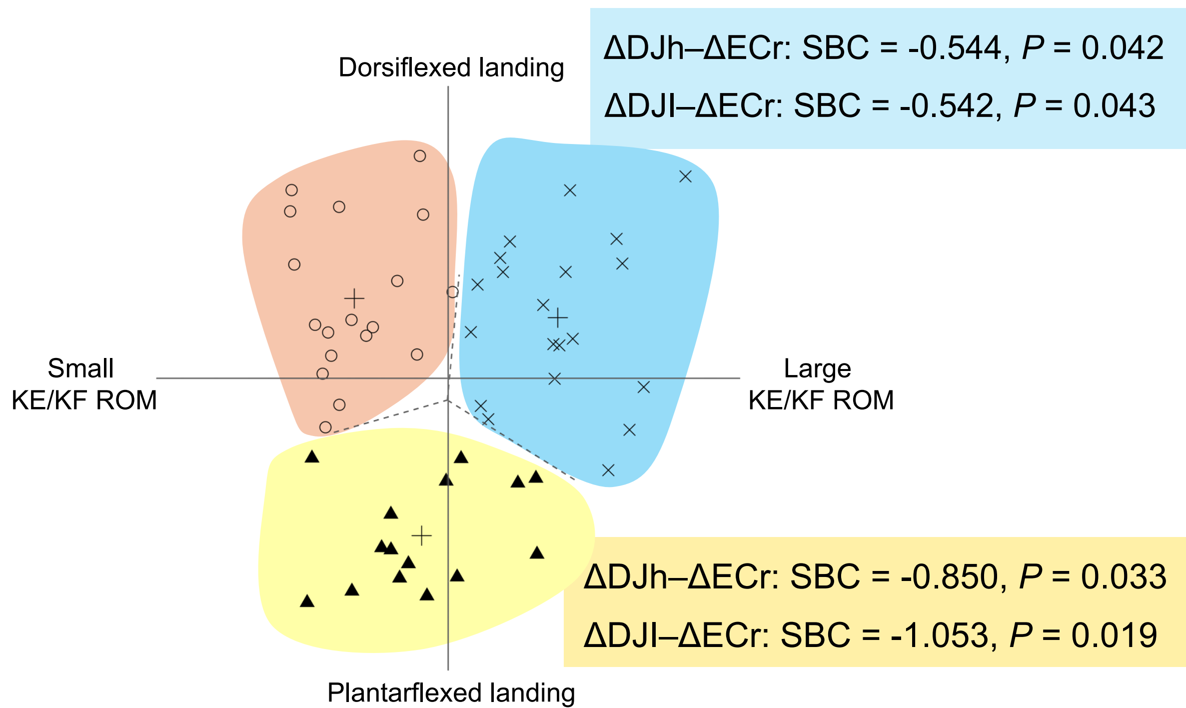


Figure 4-4. Relationships between the changes in muscle functions and running economy. Significant relationships were extracted in the figure.

Abbreviations: SBC, standardized beta coefficient; DJh, drop jump height; DJI, drop jump index; ECr, energy cost of running, KE/KF ROM, knee extension/flexion range of motion.

4-4. Discussion

In the whole (non-clustered) master endurance runners, running economy improved significantly after the plyometric training intervention. The variables most closely associated with this improvement were the interaction between gains in reactive jump performance and reductions in step frequency. When clustered by baseline running kinematics, the magnitude of running economy improvement was comparable across clusters, and enhancements in reactive jump performance generally tracked improvements in running economy, with significant associations in two clusters. Taken together, plyometric training improved running economy, and improvements in fast-SSC capacity emerged as generalizable drivers of benefit, irrespective of baseline running kinematics.

The pattern of favorable associations between drop and rebound jumps, but not CMJ, and improvements in running economy supports a temporally specific mechanism. Fast-SSC actions (< 250 ms) involve small angular excursions and brief ground contacts, whereas CMJ reflects slower SSC (≈ 500 ms) with larger excursions and longer ground contacts [62, 166, 167]. In the present study, running ground contact time ranged from 207.6 to 268.8 ms, indicating that the running task primarily engaged the fast SSC. This temporal alignment likely explains why the change in CMJ height was not significantly associated with improvement in running economy, consistent with prior work linking drop jump ability (but not CMJ height) and running economy [54]. Thus, the ability to generate force rapidly at fast-SSC time scales appears functionally relevant to improvements in running economy in master endurance runners.

Although it was expected that increases in PF torque would relate to improved running economy, as shown in resistance training in Chapter 2, no significant relationships were observed between isolated muscle strength and running economy. One explanation is that isolated muscle strength itself may not directly influence running economy [54]. Instead, muscle strength may underpin more integrated

functional capacities, such as reactive jump performance [52]. Accordingly, while muscle strength alone may not predict changes in running economy, its contribution should not be discounted, especially given evidence for the importance of lower-limb strength and the Achilles tendon stiffness in economical running [105, 135, 168, 169]. These findings also suggest that resistance and plyometric training may improve running economy through distinct neuromuscular adaptation pathways. Resistance training likely enhances running economy primarily by increasing maximal force-generating capacity and neuromuscular efficiency under high load. In contrast, plyometric training may improve the timing and utilization of elastic energy during the fast SSC. Thus, despite the lack of a direct association between muscle strength and running economy, both modalities may contribute to improved efficiency through distinct physiological mechanisms.

A significant interaction between rebound-jump height and step frequency ($P = 0.048$) indicated that runners who increased rebound-jump height while slightly lowering step frequency achieved the greatest economy gains, despite the small mean change in step frequency overall (Hedges' $g = -0.022$). Mechanistically, a lower step frequency is typically accompanied by more extended flight and shorter stance (i.e., a lower duty factor) [170], and the energetic cost of swing is estimated to be roughly one-third of stance [171, 172]. Therefore, enhanced fast-SSC capacity may reduce stance-phase cost, while a modest extension of the relatively low-cost swing further improves economy. Hence, combining strength-oriented and technique/skill training to shape running kinematics may be a fruitful avenue for improving running economy in master endurance runners.

When runners were clustered by baseline kinematics, the magnitude of running economy improvement was comparable across clusters (no significant cluster × time interaction), and two clusters showed a significant relationship between reactive jump performance gains and running economy improvement. These consistent relationships suggest that the neuromuscular functions captured by drop

and rebound jumps are fundamental determinants of running economy, regardless of baseline running motion. As noted in Chapter 3, forefoot and rearfoot strikers exhibit different muscle pre-activation strategies to absorb impact, yet both may benefit from enhanced SSC function trained through plyometric training. Thus, rather than requiring extensive tailoring based on baseline running motion, plyometric training may be broadly effective across whole runners, highlighting its utility as an effective adjunct to endurance running performance.

This study has two primary limitations, stemming from the aim to maximize sample size. First, this study did not include a control group because the primary purpose was to explore factors associated with changes in running economy, rather than to isolate the efficacy of plyometric training per se. Nevertheless, repeatability data were collected and statistically controlled for changes in running volume to account for external training effects. While a control group would have strengthened causal inference, these choices were reasonable compromises. Second, training sessions were not directly supervised. Instead, participants recorded videos that were reviewed for feedback. Although in-person supervision is generally preferred, the observed improvements in drop and rebound jump performance (but not CMJ height) suggest that video-based monitoring was effective. Notably, CMJ height is known to be less responsive to short-term plyometric training interventions than drop jumps [173], as it primarily reflects maximal strength [174] rather than neuromuscular coordination and reactive strength, as in the drop jump [175]. Overall, remote video supervision is a viable, practical alternative for monitoring plyometric training.

4-5. Summary

A 10-week plyometric program added to habitual running significantly improved running economy in master endurance runners. These gains were best predicted by improvements in reactive jump performance, a reduction in step frequency, and their interaction. Although it was anticipated that cluster-specific effects based on baseline kinematics, neither the magnitude of economy changes nor its principal correlates differed meaningfully among clusters. Mechanistically, a slightly lower step frequency is linked to shorter ground-contact and longer flight times, so enhanced SSC capacity likely reduced stance-phase cost, while the extended, low-cost swing further improved economy. In practice, plyometric training targeting reactive jump ability appears broadly effective for improving running economy, regardless of baseline running kinematics.

Chapter 5. General Discussion

This chapter synthesizes the principal findings, interprets their expected mechanistic and practical implications, and answers the thesis aims: (1) examined the effectiveness of plyometric training, as an adjunct to daily running, in improving running economy and performance compared with resistance training, and (2) investigated whether improvements in running economy and performance depend on muscle function itself or on running motion patterns that change which muscle functions become important (Figure 5-1).

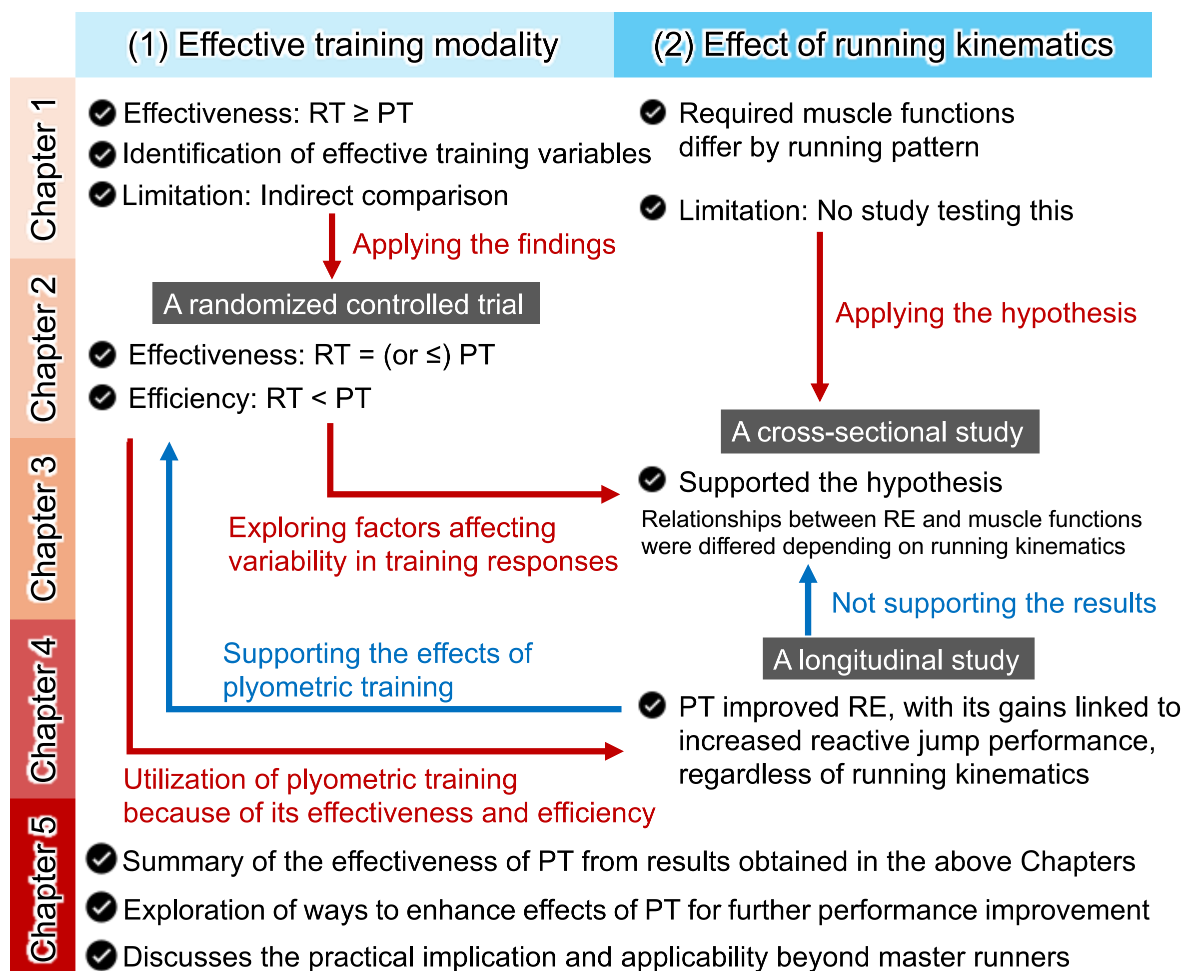


Figure 5-1. Summary diagram of the study results.

Abbreviations: RT, resistance training; PT, plyometric training; RE, running economy.

Chapter 5

5-1. Integrated summary of principal findings

In Chapter 2, plyometric training was shown to be feasible with shorter session duration, lower perceived fatigue, and no need for specialized equipment compared with resistance training, while still producing comparable (or in some cases greater) improvements in running economy and performance among master endurance runners. Moreover, improvements in running economy were significantly associated with both reductions in 5-km running time and increases in calf-raise 1RM strength, highlighting the contribution of plantarflexor strength to running efficiency.

In Chapter 3, clustering runners by foot-strike angle and KE/KF ROM during the stance phase significantly strengthened associations between muscle functions and both running economy and performance relative to the non-clustered cohort. These findings suggest that running kinematics influence which muscle groups primarily contribute to propulsion and shock absorption in master endurance runners.

In Chapter 4, adding 10 weeks of plyometric training to habitual running significantly improved running economy across all clusters of master endurance runners. A significant relationship between improvements in reactive jump performance and running economy was observed in two of the three clusters. In contrast, the remaining cluster showed a strong but non-significant association. Thus, in a longitudinal design, clustering-related differences in training responsiveness may be attenuated; nonetheless, enhancing reactive jump ability appears broadly effective for improving running economy.

5-2. The effectiveness of plyometric training on running economy and performance in master endurance runners

Evidence presented in Chapter 2 indicated that plyometric training elicited improvements in running economy comparable (or more beneficial) to those achieved with resistance training, while offering

superior practical feasibility for master endurance runners, requiring shorter sessions, inducing lower perceived fatigue, and needing no specialized equipment. Although mean 5-km performance did not change significantly during the intervention period due to a mismatch between the running velocities used for the running economy assessment and the 5-km running time trial, individual improvements in running economy were associated with improvements in 5-km run time under both training conditions. This finding suggests that gains in running economy achieved through either training modality can translate into performance benefits.

Furthermore, plyometric training in Chapters 2 and 4 produced meaningful improvements in running economy that exceeded the TE, whereas resistance training in Chapter 2 did not demonstrate a comparable magnitude of change, despite showing a significant main effect of time when analyzed together with plyometric training. Importantly, the resistance training protocol employed in this thesis would be difficult for master endurance runners to implement in practice, as it required exercising at ≥ 70% of 1RM or its equivalent (≤ 12RM), and its effectiveness generally depends on using such high loads. Taken together, these findings highlight plyometric training as an effective and practically feasible training modality for improving running economy and performance in master endurance runners.

5-3. Factors affecting the variability in running economy response to plyometric training: kinematic clusters vs. muscle function enhancements

In Chapter 3, cross-sectionally, clustering runners based on foot-strike angle and KE/KF ROM strengthened the associations between muscle functions (muscle strength and jump performance) and both running economy and performance. Consequently, it was assumed that runners differing in kinematic profiles might also differ in their responsiveness to plyometric training. Longitudinally in Chapter 4,

however, cluster-specific differences in training responsiveness were attenuated: the magnitude of running economy improvement did not differ materially between clusters, and enhancements in reactive jump performance predicted running economy gains across clusters. Thus, while baseline kinematics remain useful for diagnosis and coaching, they need not dictate the choice of training modality.

Integrating Chapters 2 and 4, changes in targeted variables (i.e., training-induced changes in muscular function) appear to drive variation in running economy improvements more than baseline running motion patterns. Among these, improvements in reactive jump performance emerged as a key determinant of enhanced running economy, reflecting more efficient utilization of the SSC and elastic energy storage at the ankle joint-Achilles tendon complex. In practice, training should therefore prioritize the development of reactive jump performance, as it directly translates into lower metabolic cost during running. Short-ground-contact plyometric training specifically targets this reactive component and is thus particularly effective for improving both running economy and performance. Where PF strength is limiting or jump metrics have plateaued despite adequate plyometric exposure, resistance training focused on enhancing PF strength can complement these adaptations. Anchoring training prescriptions to measurable variables such as reactive jump performance accommodates individual differences in responsiveness while remaining practical for master endurance runners.

Mechanistically, improvements in reactive jump performance directly translate into enhanced running performance by increasing the efficiency of force generation and energy recycling during the SSC. Runners with greater reactive jump performance can produce the necessary propulsive impulse within a shorter stance phase and with reduced muscle fiber work, thereby lowering metabolic cost [66, 160]. Consistent with this mechanism, the interaction observed in Chapter 4 between improvements in rebound-jump height and slight reductions in step frequency indicated that runners who became more reactive while marginally extending flight time achieved the greatest gains in running economy. A modestly lower step

frequency reduces the time spent in the metabolically demanding stance phase while extending the relatively inexpensive swing phase, thereby eliciting the energetic benefits of improved SSC function. To sum up, enhanced jump ability contributes to running performance by enabling more efficient propulsion through both muscular and kinematic adaptations, reducing stance-phase cost, and improving the overall energetic economy of running.

5-3-1. Exploring the characteristics associated with reactive jump performance enhancement

Several factors are likely to influence improvements in reactive jump performance: (1) lower-limb muscle strength, (2) the initial neuromuscular responsiveness to plyometric stimuli, and (3) age. First, the competitive level of runners may shape the optimal training modality for enhancing running economy and performance, partly by influencing baseline muscle strength. As discussed in Chapter 1, individuals with weaker lower-limb strength tend to exhibit longer ground contact times during drop jumps [86], reflecting lower efficiency in the SSC. In contrast, although substantial inter-individual variability in muscle strength was observed in Chapter 2, all participants were able to perform drop and rebound jumps with short ground contact times (≤ 300 ms). This suggests that the ability to execute efficient SSC actions may not depend solely on baseline muscle strength but can also be facilitated by appropriate supervision and heightened awareness of movement execution. This highlights the potential importance of coaching feedback and attentional focus of runners in eliciting optimal SSC behavior during training.

Secondly, initial acute response to plyometric training, defined as the acute pre-to-post changes in exercise performance during the first session due to early neural adaptation, likely reflects rapid neural adaptations that serve as a priming mechanism for subsequent training effects [176, 177]. Early improvements in performance may indicate heightened neural excitability and a temporarily lowered plasticity threshold, facilitating the formation of use-dependent plasticity [178]. Through dense early

repetitions, neural pathways for the practiced movements are rapidly established, enhancing coordination and motor control [179]. In the context of plyometric training, as performance improves early, each repetition may deliver a larger effective stimulus to the neuromuscular system, further amplifying adaptive responses over time. Indeed, the initial learning effect of plyometric training on drop jump performance strongly predicted training-induced improvements with approximately 85% accuracy in master endurance runners in the supplemental study of Chapter 2 (Appendix D). Previous findings also suggest that this early response can be modulated by an individual's muscle strength [180, 181]. Greater muscle strength may enhance the efficiency of neural drive transmission and the utilization of the SSC [182], thereby facilitating stronger initial neural priming and greater subsequent plasticity. Conversely, insufficient strength might limit the magnitude of the early neural response, delaying or attenuating the establishment of effective neuromuscular coordination. Taken together, these observations suggest that muscle strength not only contributes mechanically to jump performance but also plays a critical neurophysiological role in determining the sensitivity and magnitude of the initial priming response to plyometric training, which in turn influences long-term performance adaptations.

Finally, age would have some impact on the training response. Several previous studies have suggested that master runners (and/or middle-aged adults) may not gain significant increases in muscle strength from resistance training, whereas younger adults do [183, 184]. In contrast, the effects may not differ significantly by age, whereas limited studies have compared the effects of plyometric training on lower-leg muscle function (e.g., leg extension strength and jump performance) across age groups [185]. Nevertheless, the results of Chapters 2 and 4 in this thesis demonstrated significant improvements in most jump performance variables, except for CMJ in Chapter 4, suggesting that age may not substantially attenuate the adaptive responses to plyometric training. In any case, it remains unclear whether the age-related attenuation observed in resistance training responses similarly applies to plyometric training,

particularly in master endurance runners. Future studies should therefore investigate the potential moderating role of age on neuromuscular and biomechanical adaptations to plyometric training.

5-4. Other factors associated with running economy and performance improvement

Several previous studies have suggested that various factors may influence the improvement in running economy induced by resistance and plyometric training. This section explores associated factors apart from baseline running kinematics and muscle functions: (1) the performance level, (2) runners' age, and (3) changes in running kinematics.

Firstly, the influence of performance level on improvements in running economy induced by plyometric training was examined using seasonal best race times and baseline running economy values. In Chapter 2, not time-trial performance (r = -0.029, P = 0.905), but baseline running economy, showed a meaningful association with improvement in running economy (r = -0.573, P = 0.008). In addition, the data presented in Chapter 4 revealed that while marathon race time was not significantly correlated with changes in running economy (r = -0.231, P = 0.327), baseline running economy was strongly and negatively associated with improvements in running economy (r = -0.756, $P < 0.001$). These findings suggest that runners with poorer baseline running economy tend to experience greater improvements following plyometric training. In contrast, those who already exhibit high efficiency may have less room for further enhancement. If further improvement is sought in highly economical runners, it may require enhancing other physiological determinants, such as muscle oxidative capacity, tendon stiffness, or neuromuscular coordination. Therefore, baseline metabolic efficiency may be a key determinant of the magnitude of training-induced adaptation, underscoring the need for individualized, multimodal training approaches tailored to each runner's physiological profile.

Secondly, the influence of age on training-induced improvements in running economy was examined. The systematic review and meta-analysis presented in Chapter 1 indicated that the effects of resistance training on running economy tended to be greater in younger runners than in older runners, suggesting a possible attenuation of adaptation with advancing age. However, in the resistance training data in this thesis, no significant relationship was observed between age and the magnitude of improvement in running economy (r = -0.416, P = 0.068), indicating that age did not substantially affect the adaptive response to resistance training in the present cohort. Similarly, analyses of the plyometric training intervention revealed no meaningful association between age and improvement in running economy. In Chapter 2, the correlation between age and the degree of improvement in running economy was not significant (r = 0.311, P = 0.182), and a comparable result was observed in Chapter 4 (r = -0.095, P = 0.692). Taken together, these results imply that, although previous evidence suggested age-related differences in responsiveness to resistance training, the current findings indicate that both resistance and plyometric training can effectively improve running economy within master endurance runners. Therefore, both training modalities appear to be practical and effective approaches for improving running economy across a wide age range within master endurance runners.

Finally, a previous study demonstrated that changes in running kinematics induced by plyometric training can improve running economy in novice runners [186]. In Chapter 4, running kinematics was measured both before and after the intervention, and the relationships between changes in kinematics and changes in energy cost were examined. The generalized additive model (GAM) demonstrated limited explanatory power of changes in time-series joint kinematics for those in energy cost (R^2 = 0.005–0.244, P = 0.086–0.927; Appendix E). Although ankle joint angle during 0–8% of the stride significantly contributed to explaining the change in energy cost (P < 0.05), the direct association between ankle angle at touchdown and energy cost change assessed by LMM was not significant (SBC = 0.155, P = 0.480).

These findings suggest that running kinematics may be relatively resistant to modification when plyometric training is incorporated into an established routine among master endurance runners.

Importantly, the lack of a clear association between changes in jump performance and improvements in running economy in Chapter 2 supports this interpretation. These results suggest that jump performance itself may not represent the primary mediating factor linking plyometric training to improvements in running economy. Rather, the key adaptations may lie in neuromuscular mechanisms and changes in muscle-tendon stiffness that do not manifest as overt alterations in movement patterns. Plyometric training is known to enhance the efficiency of the SSC through improved pre-activation timing, increased tendon stiffness, and more effective storage and release of elastic energy during ground contact [187-190]. In trained or master endurance runners, it might be plausible that such adaptations occur primarily at the neural control level, including enhanced reflex modulation, feedforward activation, and intermuscular coordination [62, 82]. To better understand these mechanisms and to refine individualized training strategies, further research is warranted.

5-5. Applicability beyond master endurance runners

Although the present work focused on master endurance runners, the mechanisms and prescriptions identified here likely generalize to broader running populations, with sex-specific considerations noted below. First, resistance and plyometric training can improve running economy in both highly trained/elite runners and master runners. A meta-analysis in high-level middle- and long-distance runners reported large beneficial effects of adjunct resistance and plyometric training on running economy (Chapter 1). More recent syntheses across competitive levels similarly show that high-load resistance training (≥ 80% 1RM), plyometric training, and combined methods improve running economy [126]. Although no significant between-cluster differences in the magnitude of improvement in running economy were found, the overall

effect of training was substantial across all clusters. Considering this, runners with higher competitive levels, who typically exhibit lower trainability, may particularly benefit from consciously refining their running mechanics to maximize the effects of training.

Second, reactive jump performance and plantarflexor strength are key determinants of better running economy in other populations. For example, daily hopping for six weeks improved running economy in amateur runners by increasing tendon stiffness [191], and in well-trained collegiate runners, reactive jump performance, eccentric strength, and leg stiffness correlate with better running economy across speeds [54]. These results support the portability of plyometric training targeting reactive jump ability and resistance training for plantarflexor strength gains [135] to recreational, younger cohorts.

Third, sex differences appear to modify correlations between muscle function and running economy/performance. Female runners tend to rely more on knee extensors, land with a more flexed knee, and show greater eccentric quadriceps action [113, 159, 192-195], which may make KE torque a stronger correlate of running economy and performance. Indeed, in our analyses, KE torque related to both outcomes regardless of baseline running kinematics in females but not in males (under review, and unpublished data) [196, 197]. Training responses were also adequate in females: in Chapter 2, resistance training improved running economy by 2.4% in females versus 1.8% in males, and plyometric training improved running economy by 2.3% versus 3.0%, while a meta-analysis suggests sex-comparable plyometric training effects and somewhat larger resistance training effects in males [196, 197]. These findings indicate that the pathways through which training influences running economy (i.e., training for KE vs. KF) may differ between sexes, even though the overall responsiveness to training appears similar. Despite some inconsistency among studies, limited samples, and few investigations underscore the need for future research on sex-specific responses.

Overall, beyond master endurance runners, similar prescriptions are likely appropriate for most runners; baseline running kinematics should not rigidly determine the training modality. For elite runners with limited headroom, selectively considering running kinematics may yield small but meaningful performance gains. In general, programs that enhance reactive jump performance and, where indicated, increase plantarflexor strength are sound strategies for improving running economy and performance.

5-6. Effective training modality and practical application

The findings of this doctoral research collectively suggest that plyometric training represents a broadly effective and time-efficient modality for enhancing running economy and performance in endurance runners, including masters. Improvements in running economy following plyometric training were consistently associated with enhancements in reactive jump performance (e.g., drop-jump and rebound-jump height), rather than with pre-existing differences in running kinematics. This indicates that the neuromuscular ability to store and release elastic energy rapidly, namely the core of SSC function, is a key driver of metabolic efficiency during running. Practically, exercises such as jump rope, hopping, and drop jumps (using a moderate-height box) are effective for developing reactive jump ability and thereby improving running economy. Additionally, hurdle hops, which emphasize horizontal propulsion while maintaining short ground-contact times, may further facilitate running-specific adaptations [130]. Moreover, both the present doctoral research and previous studies [198] indicate that plyometric training is not only effective but also feasible and safe for middle-aged and master runners. In this study, no training-related injuries or adverse events were observed throughout the intervention period, suggesting that, when appropriately supervised and progressively introduced, plyometric training can be safely implemented even in master endurance runners.

For resistance training, improving plantarflexor strength remains a sound complementary strategy, as these muscles play a dominant role in propulsive power generation. Strengthening the plantarflexors not only supports SSC performance but also helps sustain efficiency at faster or prolonged running speeds [135]. Given that plyometric training proved effective across a wide range of runners regardless of their baseline running kinematics, similar general applicability can be expected for resistance training.

5-7. Conclusion

For master endurance male runners, plyometric training is a practical and time-efficient adjunct to habitual running, capable of improving both running economy and performance without additional training burden or equipment. Across the studies in this thesis, improvements in running economy were consistently linked to enhancements in reactive jump performance rather than to baseline running kinematics, suggesting that neuromuscular adaptations enhancing the SSC function play a primary role in improving running efficiency. The clustering analyses further revealed that while runners differ in their kinematic profiles, the effectiveness of plyometric training in enhancing running economy was consistent across groups, indicating that this modality exerts broad benefits regardless of individual movement characteristics. These findings collectively highlight that enhancing reactive strength, which is the ability to store and release elastic energy rapidly, is the key mechanism underpinning the improvement of running economy through plyometric training. Taken together, this doctoral research demonstrates that plyometric training represents a universally applicable and effective strategy for improving running efficiency in master endurance runners, providing both physiological and practical advantages for sustainable performance enhancement.

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Appendices

Appendix A. Repeatability of the variables

The trial was conducted with an interval of over one month between Trial 1 and Trial 2 to account for the wash-out period to assess the repeatability of the variables (Table A-1). During the washout period, participants were free of minor injuries and did not engage in strength training. As joint angle-related variables (e.g., ankle and knee joint angles) are continuous, the percentage values (TE [%] and minimal detectable change [MDC, %]) were not calculated. In addition, PF and DF torque were not assessed for the repeatability data.

Appendices

Table A-1. Test-retest reliability of variables measured in the doctoral thesis.

Parameters	Trial 1	Trial 2	ICC (95% CI)	TE	TE (%)	MDC_{95}	MDC_{95} (%)
Energy cost at 80% vVO_{2max} (kcal/kg/km)	0.96 ± 0.07	0.95 ± 0.08	0.928 (0.827–0.972)	0.014	1.45	0.048	5.02
Ankle angle at touch-down (°)	7.2 ± 6.3	7.9 ± 6.1	0.876 (0.711–0.950)	2.26	-	6.26	-
Knee ROM during stance (°)	30.4 ± 3.6	30.3 ± 3.5	0.938 (0.850–0.976)	0.90	-	2.50	-
Contact time (ms)	270.3 ± 12.5	270.1 ± 14.1	0.797 (0.553–0.916)	6.17	2.28	17.09	6.32
Flight time (ms)	83.8 ± 19.4	77.9 ± 19.5	0.876 (0.711–0.949)	7.12	8.50	19.75	23.56
Step frequency (step/min)	170.0 ± 9.6	173.0 ± 10.4	0.882 (0.724–0.952)	3.58	2.10	9.91	5.83
Stride length normalized height (m)	1.25 ± 0.07	1.23 ± 0.07	0.897 (0.758–0.959)	0.04	1.98	0.12	5.48
Duty factor	0.382 ± 0.022	0.389 ± 0.023	0.849 (0.657–0.939)	0.009	2.37	0.025	6.57
30°/s knee extension torque (N･m/kg)	2.54 ± 0.39	2.49 ± 0.34	0.887 (0.735–0.955)	0.128	5.05	0.356	14.00
30°/s knee flexion torque (N･m/kg)	1.22 ± 0.21	1.22 ± 0.23	0.879 (0.711–0.952)	0.079	6.51	0.220	18.03
180°/s knee extension torque (N･m/kg)	1.61 ± 0.26	1.61 ± 0.25	0.972 (0.929–0.989)	0.044	2.75	2.751	7.63
180°/s knee flexion torque (N･m/kg)	0.93 ± 0.14	0.96 ± 0.15	0.962 (0.904–0.986)	0.027	2.88	0.075	7.99
Isometric ankle plantarflexion torque (N･m/kg)	-	-	-	-	-	-	-
Isometric ankle dorsiflexion torque (N･m/kg)	-	-	-	-	-	-	-
CMJ height (cm)	37.3 ± 6.1	35.7 ± 5.4	0.878 (0.717–0.951)	2.09	5.59	5.78	15.50
Drop jump height (cm)	29.9 ± 5.1	28.7 ± 5.6	0.824 (0.607–0.928)	2.33	7.77	6.44	21.53
Drop jump index (m/s)	1.56 ± 0.36	1.52 ± 0.36	0.822 (0.601–0.927)	0.155	9.90	0.429	27.45
3-rebound jump height (cm)	27.2 ± 6.0	27.8 ± 4.9	0.891 (0.744–0.956)	1.86	6.84	5.15	18.95
3-rebound jump index (m/s)	1.46 ± 0.37	1.47 ± 0.29	0.881 (0.722–0.952)	0.118	8.10	0.327	22.45

Abbreviations: ICC, intraclass correlation coefficient; ROM, range of motion; TE, typical error; MDC, minimal detectable change; CMJ, counter-movement jump.

Appendices

Appendix B. Allometric scaling

Aerobic parameters, such as running economy and $\dot{V}O_{2max}$, in endurance runners have commonly been expressed as relative values normalized to body mass (i.e., ratio-metric values) [32, 35, 66], since a strong relationship has been shown between body mass and absolute $\dot{V}O_{2max}$ in athletes [199, 200]. Traditionally, these parameters have been normalized to body mass using ratio scaling (e.g., mL/kg/min), assuming a proportional relationship between body size and aerobic capacity. However, this assumption is not always valid [201], especially at submaximal intensities or among diverse populations [202-205]. Allometric scaling, which expresses physiological variables as a power function of body mass ($B = aM^b$), offers a more flexible and accurate approach [147, 206]. The allometric exponent (b) can vary with factors such as sex, age, and sport discipline, and using a fixed value, such as 0.75 (Kleiber's Law), may lead to inaccurate normalization [207]. Therefore, determining the exponent within the specific population being studied is recommended to account for physiological variation and optimize comparisons.

Residual correlation is a method used to evaluate whether a scaling method effectively removes the influence of body mass [208, 209]. A low or absent residual correlation indicates appropriate scaling. Several previous studies have shown that using calculated allometric exponents yields stronger associations with performance than simple ratio scaling [210-212]. Despite the importance of scaling, only one prior study has examined its impact on the relationship between running economy and performance, and it was limited by a small sample size and a lack of residual analysis [213]. Thus, the importance of using the population-specific allometric scaling remains unclear in endurance runners.

Determination of the Scaling model.

Relationships between the energy cost or $\dot{V}O_{2max}$ and body mass were similarly fitted by both linear ratio scaling and power functions, as indicated by comparable R^2 and RMSE values for both aerobic variables

(Figure B-1). The calculated allometric exponents of the aerobic parameters based on the power function were b = 0.839 for the energy cost of running at 80% of $v\dot{V}O_{2max}$ and b = 1.217 for $\dot{V}O_{2max}$. In contrast, the residual correlation between the power function ratios (B/M^b) and body mass (M) was not practically meaningful (r = -0.002 and -0.004) in the calculated allometric exponents based on the power function (Table B-1). Practically meaningful residual correlations were observed in the other two allometric exponents: r = -0.316 for the energy cost and 0.224 for $\dot{V}O_{2max}$ in ratio scaling (b = 1) and r = 0.184 for the energy cost and r = 0.449 for $\dot{V}O_{2max}$ in Kleiber's exponent (b = 0.75) (Figure B-2).

The parallelity of the regression lines for the energy cost of running at 80% of $v\dot{V}O_{2max}$ and $\dot{V}O_{2max}$ was confirmed in sex (P = 0.755 and 0.571), age (P = 0.823 and 0.128), and season's best (P = 0.144 and 0.425), respectively, indicating that these had no significant effects on allometric exponents. Consequently, the appropriateness of using the calculated allometric exponents based on the power function model and mixing all runners into the scaling model was confirmed.

Appendices

Table B-1. The calculated allometric exponents for the aerobic parameters, residual correlations between the power function ratios (B/M^b) and (M), and adjusted R^2.

	Calculated allometric exponent	Residual correlation	Adjusted R^2
Energy cost of running at 80% $v\dot{V}O_{2max}$ (kcal/kg^b/km)	b = 0.839 (0.754–0.929)	r = -0.002 (-0.179–0.182)	0.783
$\dot{V}O_{2max}$ (mL/kg^b/min)	b = 1.217 (1.047–1.388)	r = -0.009 (-0.187–0.169)	0.626

The data were shown as values and 95% CIs, except for adjusted R^2.

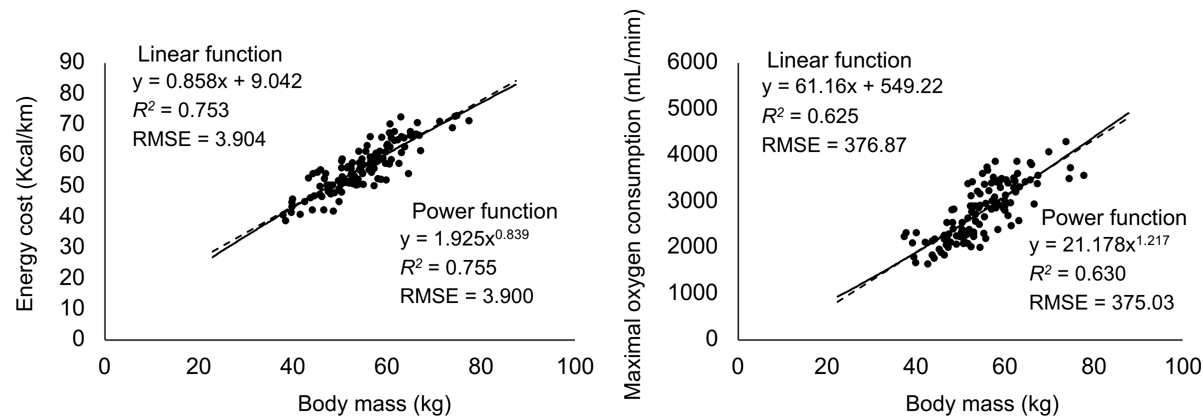

Figure B-1. Comparison of linear (dashed line) and power (solid line) function fits for the relationship between energy cost or $\dot{V}O_{2max}$ and body mass. The relationships between energy cost or $\dot{V}O_{2max}$ and body mass were fitted using both linear and power functions. The figure illustrates the differences in model fitting, showing how each function represents the data trend.

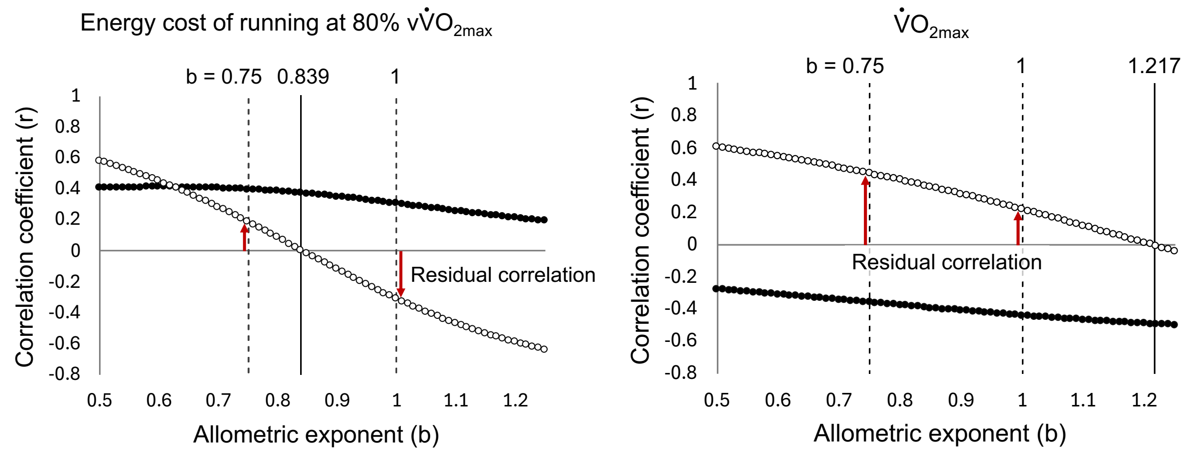

Figure B-2. The shift of the residual correlation coefficients between power function ratio (B/M^b) and body mass (M) (open circle), and that of the relationships between aerobic parameters and season's best (closed circle) while varying the value of the allometric exponent from 0.5 to 1.25 in increments of 0.01.

Appendices

Assessment of aerobic parameters.

The relationships between the energy cost of running at 80% of $v\dot{V}O_{2max}$ or $\dot{V}O_{2max}$ and the season's best did not significantly differ among the three allometric exponents ($P = 0.558–0.954$; Table B-2). No significant differences in the energy cost of running at 80% of $v\dot{V}O_{2max}$ were found among the three performance levels (bottom, middle, and top) when scaled using the ratio scaling ($P = 0.093$; Figure B-3). In contrast, the energy cost of running was significantly different between the top and bottom levels when scaled with Kleiber's ($P = 0.008$) and calculated ($P = 0.018$) exponents. $\dot{V}O_{2max}$ significantly differed between the top level and both the middle and bottom levels, regardless of the choice of allometric exponents ($P < 0.001$; Figure B-3).

Table B-2. The relationships between the aerobic parameters and seasonal record, while varying the scaling methods.

	Ratio scaling (b = 1)	Kleiber's exponent (b = 0.75)	Calculated allometric exponent
Energy cost of running at 80% $v\dot{V}O_{2max}$ ($kcal/kg^b/km$)	*r* = 0.301 (0.125 to 0.464)	*r* = 0.393 (0.222 to 0.541)	*r* = 0.369 (0.196 to 0.519)
$\dot{V}O_{2max}$ ($mL/kg^b/min$)	*r* = -0.580 (-0.708 to -0.428)	*r* = -0.554 (-0.686 to -0.401)	*r* = -0.575 (-0.703 to -0.424)

The data were presented as correlation coefficients and 95% CIs.

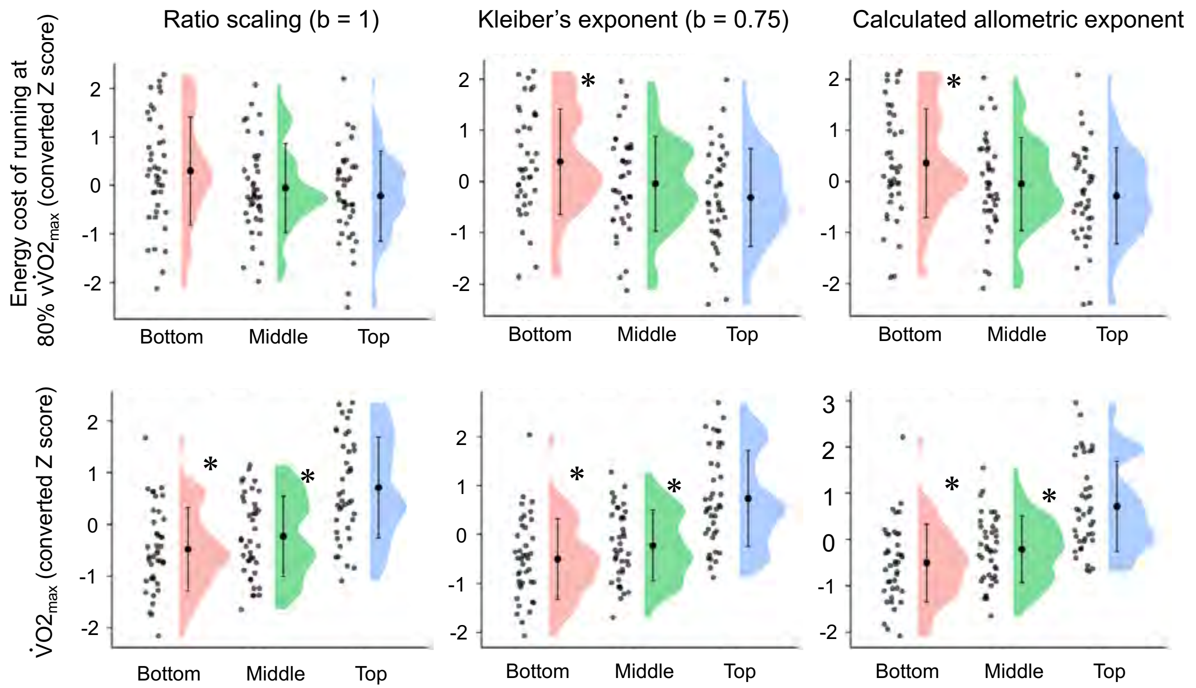

Figure B-3. The difference in aerobic parameters converted for *Z*-score among the performance levels (top vs. middle vs. bottom levels) in each scaling method.

* represents a significant difference ($P < 0.05$) to the top level.

The linear and power functions provided a comparable fit for both running economy and $\dot{V}O_{2max}$. Still, the calculated allometric exponent based on the power function showed smaller residual correlations than ratio-scaling (b = 1) and Kleiber's exponent (b = 0.75). This suggests that using the calculated allometric exponents can accurately assess aerobic capacity without over- or underestimating aerobic parameters. Consequently, the choice of allometric exponent would affect the interpretation of group comparisons for running economy across the performance levels (main effect of group: $P = 0.008–0.093$) while it had no significant influence on the relationships between aerobic parameters and running performance (difference in r value: $P = 0.558–0.954$). Although the statistical impact of the allometric exponents on correlation coefficients was limited, their influence on the interpretation and conclusions of group comparisons was substantial. This highlights that even small numerical differences in scaling exponents can meaningfully alter conclusions, particularly in comparisons of running economy across groups. Thus, the doctoral thesis used allometric scaling to normalize aerobic parameters in Chapter 3 to assess the relationships between running economy and muscular function.

Appendices

Appendix C. Simulation of the move across clusters

In Chapter 3, the cluster analysis had a potential vulnerability, as clusters were determined based on participants' relative positions. Therefore, the extent to which cluster transitions (changes) would occur when additional data were introduced was investigated. As shown in Figure C-1, the data labeled as 0 or 1 changed clusters in over 80%. This indicates that even when new data are added, the relative positions of the original data remain almost unchanged.

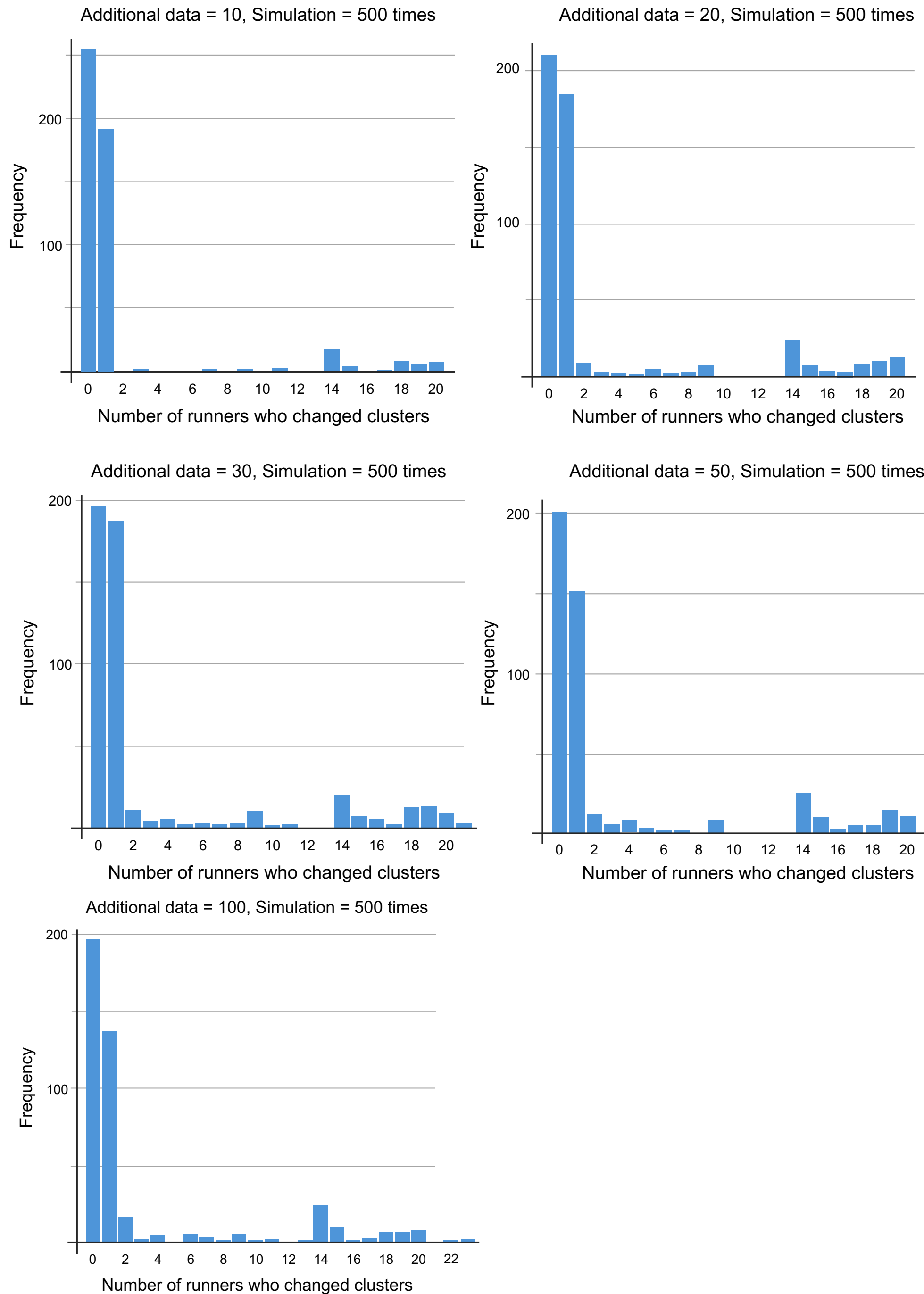

Figure C-1. The stability of clustering results with bootstrapped additional data. Cluster transition frequency when adding synthetic data points (10, 20, 30, 50, and 100) with ±0.2SD random noise to the Chapter 3 dataset. Clustering was repeated 500 times using the bootstrap method. The figure shows the proportion of runs in which each original data point changed its cluster assignment, indicating the robustness of the clustering structure against data expansion.

Appendices

To examine the changes in running kinematics following training, post-training data were then projected onto the same graph using the pre-training dataset in Chapter 3. Four runners crossed the cluster boundaries; however, the visualization revealed that most runners remained in their original clusters (Figure C-2). In addition, the shapes of each cluster, the improvement in running economy, and the associated factors remain similar (Figure C-3). In other words, there was a significant difference in the improvement in running economy, and the increased reactive jump performance was significantly associated with the improved running economy in all clusters, as shown in Chapter 4.

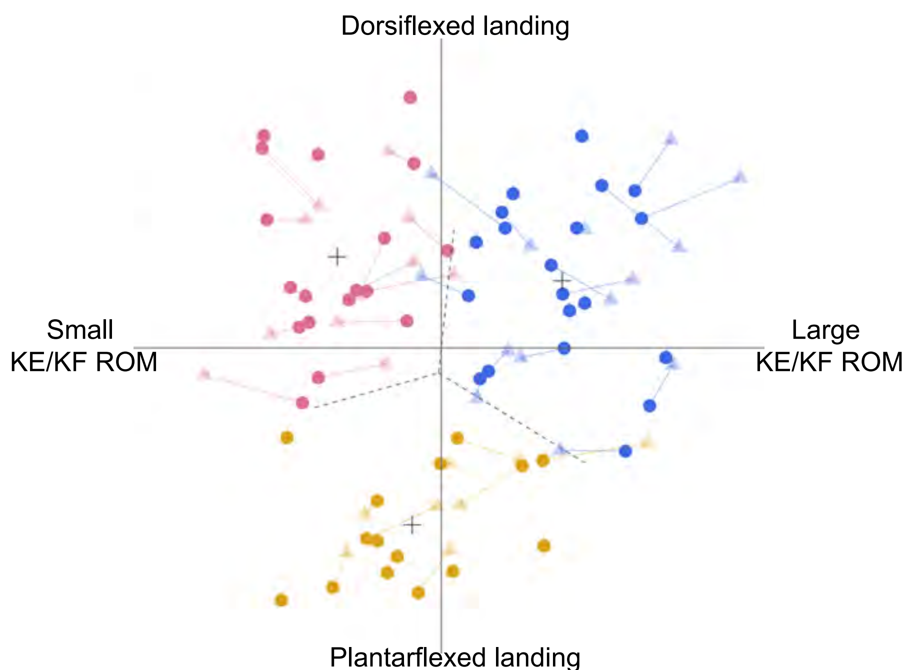

Figure C-2. Pre- and Post-Training Joint Angle Changes by Cluster. Pre-training joint angles (●) and post-training joint angles (▲) plotted for each runner, grouped by cluster assignment. Arrows indicate the directional change in standardized foot-strike angle and KE/KF ROM from pre- to post-training. Voronoi boundaries and cluster centroids are shown to visualize group structure and stability.

Abbreviation: KE/KF ROM, knee extension/flexion range of motion.

Appendices

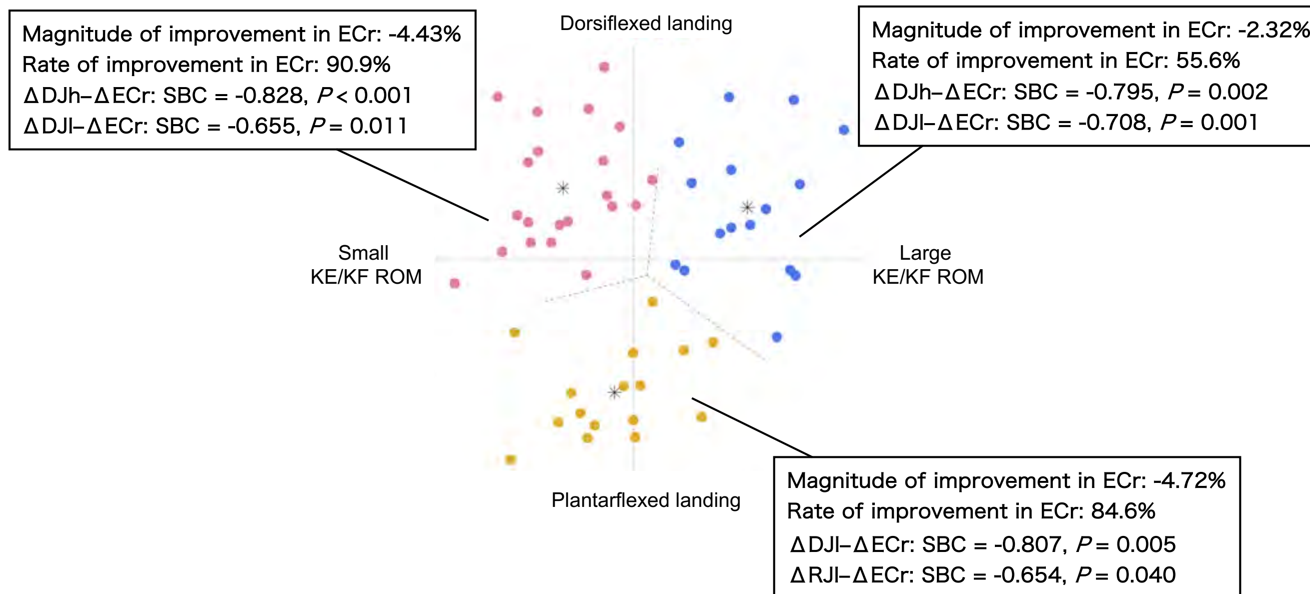

Figure C-3. Factors associated with the energy cost of running and WA score when runners are classified based on running kinematics at 80% $v\dot{V}O_{2max}$. Foot strike angle and KE/KF ROM during the stance phase were converted into a *Z*-score. Significant relationships are highlighted within the rectangles. The values in the rectangle represent SBC between muscle functions and either the energy cost of running or its *P*-value.

Abbreviations: KE/KF ROM, knee extension/flexion range of motion; DJh, drop jump height; DJI, drop jump index; RJI, rebound jump index; ECr, energy cost of running; SBC, standardized beta coefficient.

Appendices

Appendix D. Effects of initial acute response on plyometric-training-response

This supplementary analysis investigated whether initial acute responsiveness to plyometric exercise predicts subsequent training-induced improvements in drop-jump performance. Drop jump performance has been linked to endurance running performance [34], and such actions require coordinated muscle activation [214]. Therefore, neural adaptation is likely to play an essential role in performance enhancement. Previous studies have shown that initial acute responsiveness, defined as the immediate pre-to-post change in performance during the first training session, can predict long-term motor learning [177]. However, these findings were based primarily on upper-limb, non-ballistic tasks and may not directly generalize to lower-limb ballistic movements such as drop jumps.

To test this relationship, data from ten master endurance runners (three females) in the plyometric training group described in Chapter 2 were analyzed. Drop jump height and index were measured immediately before and after each weekly training session, as well as before and after the 10-week intervention period. Repeated-measures correlation analyses and LMM were used to examine the association between initial acute changes (Week 1 pre-to-post differences) and training-induced improvements over 10 weeks. The results showed that the initial acute responsiveness in drop jump height (+3.72 ± 3.22 cm) and index (+0.27 ± 0.20 m/s) were significantly correlated with the magnitude of the training-induced improvements in the same variables ($r = 0.831$, $P < 0.001$ for height; $r = 0.813$, $P < 0.001$ for index). The corresponding LMM explained the majority of variance in these relationships (conditional $R^2 = 0.862$ for height and 0.849 for index, $P < 0.001$). These findings suggest that early neural responsiveness to plyometric exercise may serve as a useful indicator of subsequent trainability in drop jump performance among master endurance runners. Thus, initial acute response to plyometric training on drop jump performance can strongly predict training-induced improvements in drop jump performance with approximately 85% accuracy in master endurance runners.

Appendices

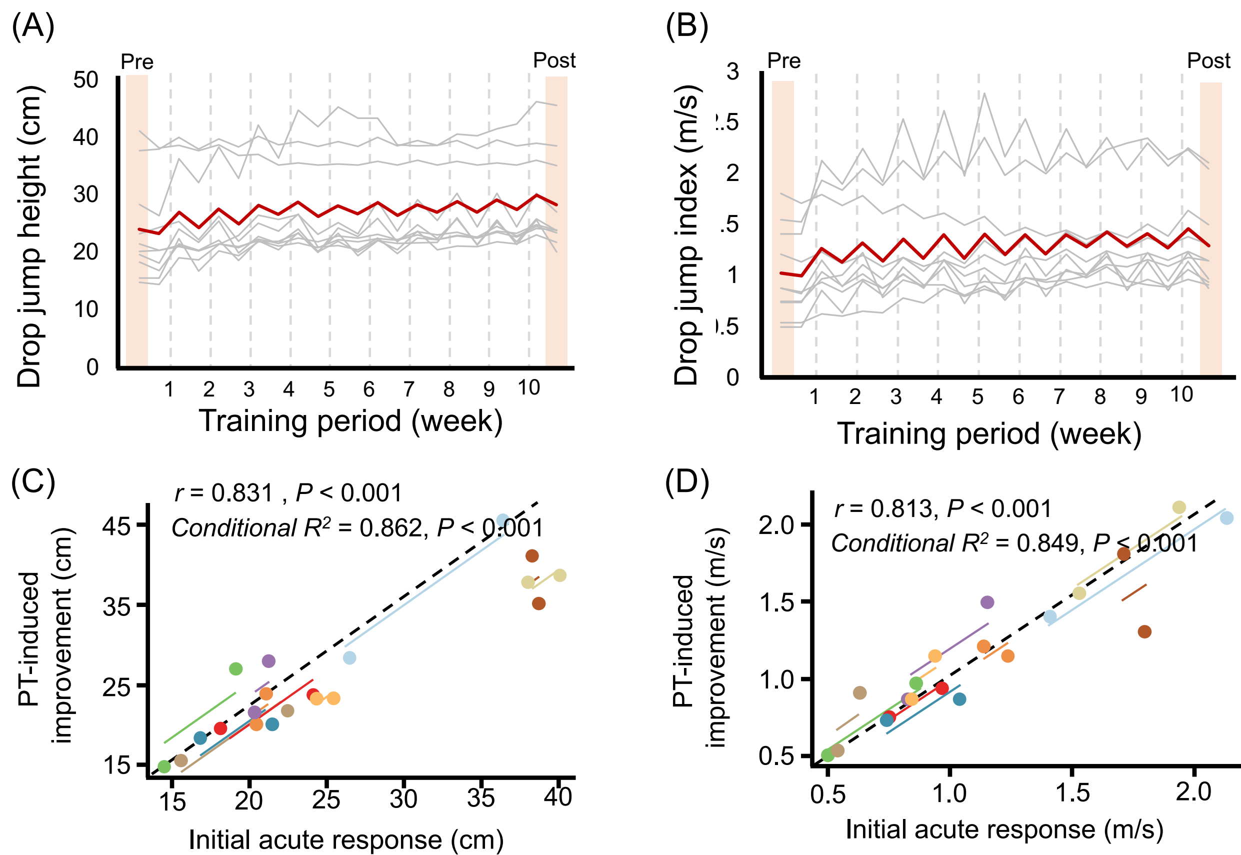

Figure D-1. Weekly changes in drop jump height (A) and index (B), and the relationships between initial acute responsiveness and overall (pre-to-post) training-induced changes (C & D). Drop jump performance (A & B) was assessed before and after each weekly training session.

Abbreviation: PT, plyometric training.

Appendices

Appendix E. Effects of changes in running kinematics on running economy improvement induced by plyometric training

To examine the extent to which changes in running kinematics contributed to improvements in running economy following plyometric training, GAMs were constructed using time-series joint-angle data as predictors of changes in energy cost in Python (Spyder 6.0.7). The analyses demonstrated limited explanatory power of kinematic changes for variations in energy cost (R^2 = 0.005–0.244, P = 0.086–0.927; Figure E-1). Among the examined variables, the ankle joint angle during the early stance phase (0–8% of the stride) significantly contributed to explaining the change in energy cost ($P < 0.05$). However, the direct relationship between ankle angle at touchdown and the change in energy cost, assessed by an LMM, was not significant (SBC = 0.155, P = 0.480; Figure E-2). These results suggest that, while localized changes in ankle kinematics may transiently relate to energy-cost adaptation, the overall modification of lower-limb joint angles across the stride cycle exerts a limited influence on the improvement in running economy following plyometric training.

Appendices

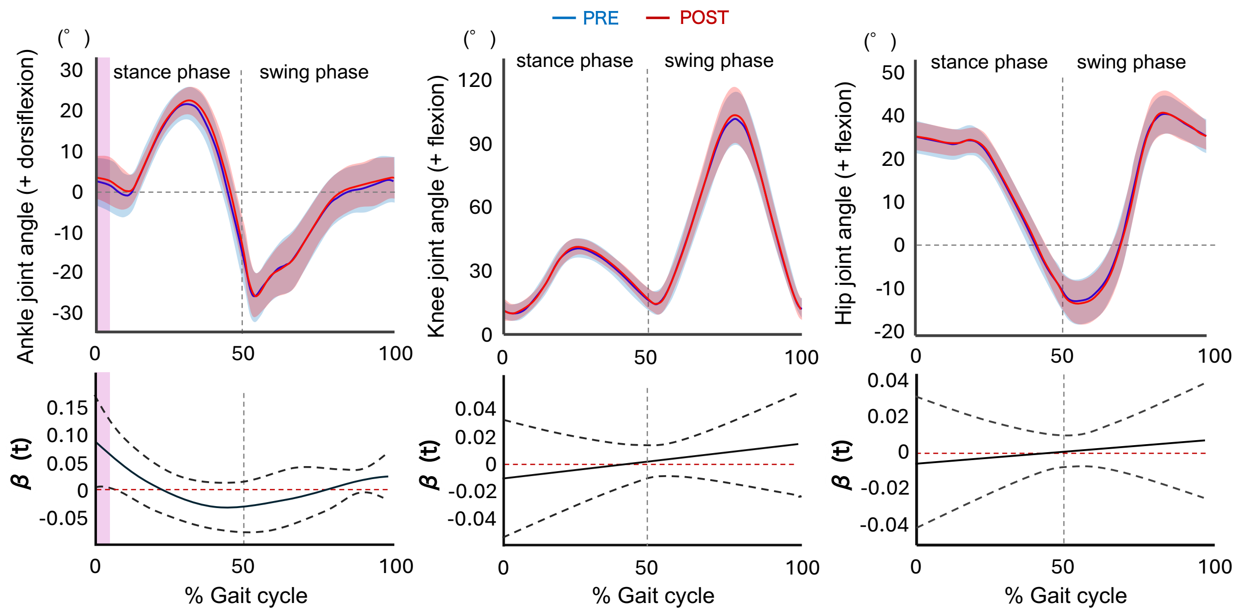

Figure E-1. Pre- to post-intervention changes in the sagittal-plane joint kinematics during running in the plyometric training dataset. Time-series data of sagittal-plane joint angles (hip, knee, and ankle) during one gait cycle at 80% $v\dot{V}O_{2max}$ are shown for pre- and post-training conditions. Blue and red curves represent group means for pre- and post-training, respectively, with shaded areas denoting SEs. The shaded area in the ankle joint graph indicates the time interval during which the change in joint angle significantly contributed to the change in energy cost of running ($P < 0.05$), as identified by the generalized additive model (GAM). In this analysis, β(t) represents the time-varying regression coefficient quantifying the strength and direction of the relationship between changes in joint angle at each time point and the overall change in running energy cost.

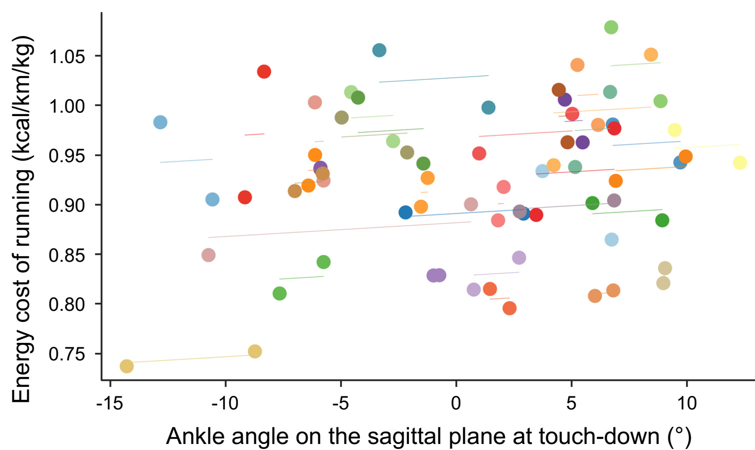

Figure E-2. The relationship between changes in ankle joint angle at touch-down and energy cost of running.

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