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Systematic review

Biomechanical factors associated with running economy and performance of elite Kenyan distance runners: A systematic review

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A B S T R A C T

Background: Running economy (RE) is a determinant of performance in endurance sports and is a complex multi-factorial measure which reflects the combined functioning of bio-mechanical, neuro-muscular, metabolic and cardio-respiratory factors some of which are hereditary or adapt to coaching. Kenyan distance runners have dominated major global events with their unmatched performance for decades and this phenomenon has prompted several investigations aimed at establishing possible factors associated with their performance. This systematic review was aimed at establishing up-to date quantitative synthesis of evidence on biomechanical factors associated with running economy and performance of elite Kenyan distance runners and to provide an algorithm for future research and coaching strategies.

Methods: A comprehensive electronic search was conducted through June 2017. Quality appraisal was independently done by both reviewers using the STROBE checklist. Descriptive summaries and tables were used to illustrate biomechanical outcomes, mean differences and confidence intervals. Evidence from reviewed studies was graded according to the Australian National Health and Medical Research Council (NHMRC) hierarchy for aetiological factors and meta-analysis was performed where applicable.

Results: Eight cross-sectional studies were included. The overall methodological score was moderate (58%). Elite Kenyan distance runners have significant longer gastroc-Achilles tendons compared to their counterparts while their shank length is not significantly longer. There is no certainty of evidence regarding the association between their characteristic unique profile of tall and slender bodies, low BMI and low body mass, short ground contact and flight times, greater forward lean torso and faster and greater forward leg swing with RE and performance.

Conclusion: Our findings presents evidence on biomechanical factors associated with RE and performance of elite Kenyan distance runners. Despite these findings, there are a number of limitations inherent to this review including; low level of evidence, minimal number of included studies, small sample size and lack of appropriate control subjects. However, we considered these shortcomings and summarised the best available evidence in attempt to give direction to future research and coaching strategies.

1. Background

Running economy (RE) is a predictor of performance in distance running (Saunders et al., 2004) and is defined as the steady-state oxygen consumption (V_O2) at a given submaximal running velocity and a measure of energy cost of running. RE is a complex multi-factorial measure which reflects the combined functioning of bio-mechanical and neuro-muscular factors as well metabolic and cardio-respiratory factors. Bio-mechanical and neuro-muscular efficiency refers to the inter-action and ability to convert muscular power output into translocation and therefore performance. Genetic heritability of determining factors for performance has been

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suggested as well as modification and adaptation of factors through coaching strategies. Therefore, RE is an important measure of athletic performance to coaches, scientists, practitioners and runners, and reliable measures and values for different calibre of athletes have been documented in literature.

Several factors have been suggested to contribute to the RE and performance of elite Kenyan endurance runners, including superior genetic endowment, physiology, environment, biomechanics, diet, living and growing up at altitude among others (Wilber and Pitsiladis, 2012; Larsen, 2003). Similarly, theories of a possible complex integrated combination of intrinsic (genetic and biological) and extrinsic (environment, training, motivation) factors have been suggested to argue their performance (Tucker et al., 2013; Wilber and Pitsiladis, 2012) even though there is no substantive scientific evidence to confirm or disapprove the contribution of the various factors.

There exist scientific evidence regarding metabolic and cardiorespiratory factors that affect RE. These factors include; mitochondrial efficiency, heart rate (HR), minute ventilation (V_E), thermoregulation core temperature (C_{Temp}) and muscle fibre type (Saunders et al., 2004), but there is no consensus on biomechanical factors which have influence on RE probably because it appears that runners with varied biomechanical profiles tend to have better RE.

East African distance runners particularly Kenyans have for the past four decades emerged dominant in the international scene in medium- and long-distance races. Their extra-ordinary dominance in medal standings, all time world records and IAAF rankings is so far unmatched by any other population in any sport globally and has since been termed as the greatest geographical concentration of sports excellence in the annals of sports (Larsen and Sheel, 2015). The global unparalleled performance of Kenyan distance runners has prompted questions and research undertakings among scientists in the fields of exercise physiology and sports [2].

Previous narrative reviews (Larsen and Sheel, 2015; Wilber and Pitsiladis, 2012; Tucker et al., 2013; Saunders et al., 2004) focused on assessing available evidence on both genetic and physiological factors among Kenyan distance runners, and the conclusion was that Kenyan distance runners do not possess a unique genetic make-up or physiology. Several primary observational studies (Mooses et al., 2014, Sano et al., 2015; Kunimasa et al., 2014; Lieberman et al., 2010) have examined their biomechanical characteristics including; foot strike patterns, ground reaction forces, muscle-tendon architecture and interaction, running gait cycle characteristics and anthropometrics. To our knowledge, no systematic literature review has been conducted to quantitatively analyse the biomechanical factors associated with running economy and performance of Kenyan distance runners. Therefore, in this review we aimed at firstly; to present up-to date quantitative evidence synthesis relative to biomechanical factors among elite Kenyan distance runners, and secondly, to provide an algorithm for future research and coaching strategies pertaining to biomechanical factors associated with RE and performance.

2. Methods

Data from published studies written in English and reporting on biomechanical factors among elite Kenyan distance runners were included in this review. Studies were included if they were conducted to determine biomechanical factors among elite male and female Kenyan distance runners. Studies were excluded if they investigated other factors like genetics and physiology, or those which enrolled non-elite Kenyan distance runners.

A comprehensive search of various electronic databases was done from inception until June 2017. The search strategy used was as follows; "*biomechanical AND factors OR determinants OR characteristics AND running economy AND performance OR excellence AND elite OR professional AND Kenyan AND distance OR endurance AND runners OR athletes*". The specific data bases which were searched include; Ebsco host, Medline, CINAHL, Springer, Sports Discuss, Pubmed and google scholar. In order to maximise the total hits, hand-searching (pearling) of reference lists of published and relevant reviews and full text of potentially eligible articles was conducted by the first reviewer (NT).

Full text records of studies which were deemed eligible as per the inclusion criteria were retrieved for screening. The first reviewer (NT) independently screened the title and abstract of all initial total records using the inclusion criteria and the findings were discussed with the second reviewer (QL) and disagreements were resolved through a consensus meeting. The STROBE checklist was used to appraise the methodological quality of included studies. This tool was used since it clearly gives the specific items to be assessed in observational studies. The STROBE checklist guideline was used by both reviewers in order to familiarise themselves with the process of quality appraisal. The first reviewer (NT) independently appraised all included studies and the second reviewer (QL) cross-checked the results and discrepancies and queries on the findings were discussed until consensus was reached. Following the methodological appraisal, all included studies were rated according to their methodological quality as illustrated in Table 3. A reviewer-developed structured data capture excel spreadsheet (Table 2) was used for data extraction from the 8 eligible studies. Data extraction for each study included, author, year, country, setting, sample size, participants' characteristics, data collection tools, data collection procedure, outcome measures, key findings and conclusion.

The FORM framework was used to grade the available evidence and provide recommendations regarding biomechanical factors associated with running economy and performance in distance running. For the purpose of this review, two (evidence base and consistency) of the five elements were utilised because these elements are in line with the aim of the current review. Evidence refers to the quantity and quality of the studies which were included in the current review in relation to the review question while consistency refers to the homogeneity of findings across included studies. The level of evidence was graded according to the Australian National Medical and Health Research Council (NMHRC) hierarchy for aetiology which is presented in Table 8. Data is described quantitatively and narratively using tables and summaries, and where possible, forest plots statistical modelling was used to conduct meta-analysis of pooled data from homogenous using the *Revman 5* software.

3. Results

The electronic search which was conducted through June 2017 yielded total hits of 98 articles. After removal of duplicates and application of inclusion and exclusion criteria, 63 articles were disqualified hence reducing the total records to 35. Further to that, 27 articles were disqualified after reading the abstracts. The primary purpose for excluding these studies was that they investigated other factors like genetics, physiology, nutrition, hydration practices and training. Similarly, some of the excluded studies were conducted among none elite Kenyan distance runners. After reading the full text of the remaining studies, a total of 8 articles met the inclusion criteria and were analysed in this review. These studies investigated various aspects of biomechanical factors which are associated with running economy and performance of elite Kenyan distance runners. Fig. 1 below represents schematics of the search procedure which was followed in the review process (see Table 1 and Fig. 2).

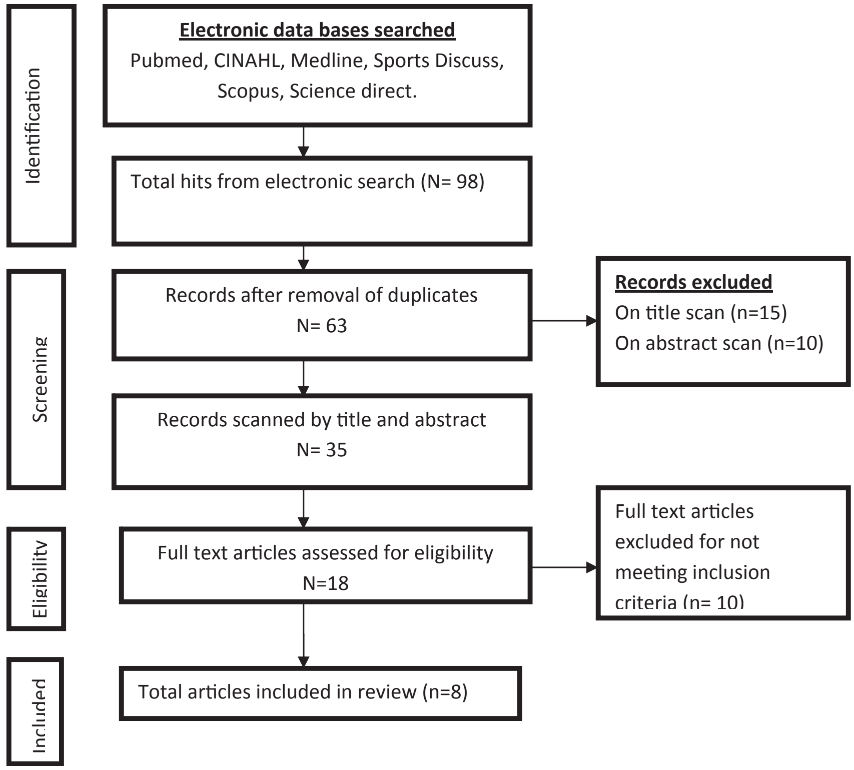

Fig. 1. Flow diagram of literature search.

The eight articles which are included in this review were published between the year 2008–2016, and a comprehensive description of the sample of each included study is provided in Table 2 including participants' gender distribution and mean; age, height, body mass and their distance running performance rating by the International Armature Athletic Federation (IAAF). Similarly, the characteristics of all included studies, including the study design, aim of the study, study setting, key findings and final conclusions drawn are presented in Table 3. In this review, the biomechanical factors which were investigated include; anthropometrics, joint kinematics, joint kinetics, lower limb muscle strength, gait cycle characteristics, running motion, lower limb muscle-tendon inter-action and pre-activation and general lower limb soft tissue characteristics. The reviewed studies observed different biomechanical factors among elite Kenyan distance runners compared to elite; Japanese, American, Caucasians and Ethiopian runners.

The reviewers (NT and QL) independently assessed the included studies for methodological soundness using the STROBE checklist. The quality of included studies ranged from 43% to 71% with a mean score of 58%. All included studies satisfied the following items on the criteria; *1, 2, 5, 13, 18* and *20*, while on the other hand, none of the included studies met the criteria for items *10, 16* and *17* which means they did not provide satisfactory details about the study size estimation, statistical methods, and un-adjusted estimates of main results respectively. Table 3 presents the methodological quality scores for all included studies.

3.1. Anthropometrics

Seven studies (Santos-Concenjero et al., 2016; Sano et al, 2013, 2015; Mooses et al., 2014; Kunimasa et al., 2014; Sano et al., 2013; Lieberman et al., 2010 and Kong and de Heer, 2008) analysed anthropometric measures. The factors investigated were; height, weight, body mass, body mass index, Achilles tendon length, Achilles tendon moment arm, shank, length, thigh length and total body fat composition. Apart from the study by Kong and de Heer (2008), the other studies reported use of valid and reliable

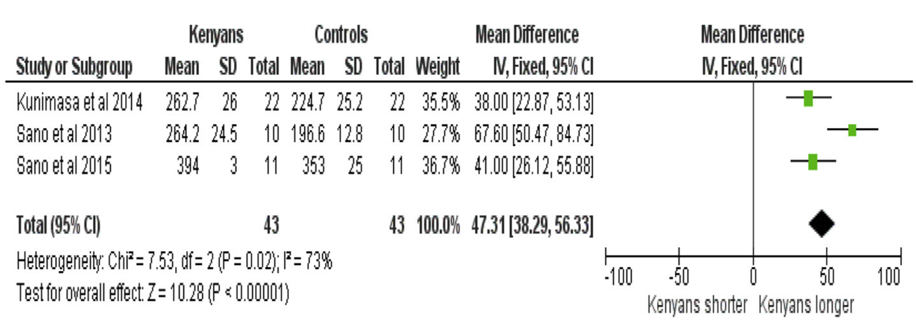

Fig. 2. Meta-analysis of Gastroc-Achilles tendon length (cm).

Table 1
Sample description.

	Sample size (N)		Gender		Mean age, years (SD)		Mass, kg (SD)		Height, m (SD)		IAAF Score	
	K	C	K	C	K	C	K	C	K	C	K	C
Santos-Concenjero et al. (2016)	15	0	15M 0F	0	23.7 (4.2)	0	NR	NR	NR	NR	NR	NR
Sano et al. (2015)	11	11 (Japanese)	NR	NR	19.3 (3.1)	19.6 (2.4)	56.0 (7.1)	58.3 (4.8)	1.74 (7.9)	171.2 (4.3)	1126.9 (105.2)	909.4 ()130.8
Mooses et al. (2014)	32	0	32M 0F	0	25.3 (5.0)	NA	56.5 (5.7)	NA	1.72 (0.07)	NA	993 (77)	NA
Kunimasa et al. (2014)	22	22 (Japanese)	NR	NR	21.9 (4.5)	20.2 (2.2)	57.2 (4.8)	56.9 (0.05)	1.74 (0.06)	1.73 (0.05)	1130.0 (91.3)	1004 (49.8)
Sano et al. (2013)	10	10 (Caucasians)	10M 0F	10M 0F	21 (4)	25 (4)	57.9 (5.1)	71.3 (5.0)	1.75 (0.06)	1.74 (0.05)	NR	NR
Lieberman et al. (2010)	47	16(Americans)	31M 16F	13M 3F	23.1 (3.5)	19.1 (0.4)	NR	NR	NR	NR	NR	NR
Enomoto et al. (2008)	1	2 (Ethiopians)	1M	2M	NR	NR	52	54.5	1.67	1.66	NR	NR
Kong and de Heer (2008)	6	0	6M	0	22.0 (1.8)	NA	63.0 (7.3)	NA	1.77 (0.06)	NA	NR	NA

Abbreviations: M Male, F Female, NR Not reported, NA Not applicable, K Kenyans, C Controls.

Table 2
Characteristics of included studies.

Author (year)	Study design	Study aim(s)	Study setting	Main findings
Santos-Concenjero et al. (2016)	Descriptive cross-sectional	To determine whether gait cycle characteristics are associated with running economy	Kenya (Field-study)	No association between gait cycle characteristics, GRFs and running economy. However, the ground contact time among Kenyan runners was considerably different (shorter) compared to that reported in literature. This may contribute to the exceptional running economy of Kenyan runners.
Sano et al. (2015)	Analytical cross-sectional	To analyse leg muscle activation profile and muscle-tendon interaction between Kenyan and Japanese runners	Kenya and Japan (Laboratory-based)	At each running speed, both groups presented similar contact and flight times. During ground contact, Kenyans demonstrated smaller stretching and shortening amplitudes of the tendinous tissue of Medialis Gastrocnemius (MG) but greater tendon contribution to the muscle-tendon unit shortening. EMG showed lower braking/pre-activation ratio of MG and TA among Kenyans.
Mooses et al. (2014)	Descriptive cross-sectional	To investigate the relationship between running economy and performance among Kenyan elite distance runners.	Kenya (Laboratory-based)	Achilles moment arm and long legs are associated with running performance but, a superior running economy could not account for performance of Kenyan runners.
Kunimasa et al. (2014)	Analytical cross-sectional	To characterise the Achilles tendon moment arm and examine relationship with running performance between Kenyan and Japanese runners.	Japan (Laboratory-based)	Kenyan runners had significantly longer Achilles moment arm and lower foot lever compared to their Japanese counterparts.
Sano et al. (2013)	Analytical cross-sectional	To determine the muscle-tendon characteristics.	Kenya (Laboratory-based)	Kenyan runners had long gastro Achilles tendons (absolute and relative values) compared to Japanese. Kenyans had greater shortening to stretching ratio of gluteus medius implying an efficient use of tendinous elasticity for a better hysteresis.
Lieberman et al. (2010)	Analytical cross-sectional	Analysis of foot kinematics and kinetics in barefoot and shod Kenyan and American runners.	Kenya (Track-based)	Barefoot Kenyan runners land with fore foot strike or mid-foot strike compared to shod runners who land with Rare foot strike. Barefoot runners therefore generate less ground collision forces due to a more planter-flexed fore toot.
Kong and de Heer (2008)	Descriptive cross-sectional	To determine anthropometric, gait and lower limb strength of elite Kenyan distance runners	United States of America (Laboratory-based)	Elite Kenyan distance runners are characterized by a low BMI, low percentage body fat and slim limbs, short ground contact time with shorter time during right foot contacts. Their leg strength was relatively low compared to other runners, but they possessed high

Table 2 (*continued*)

Author (year)	Study design	Study aim(s)	Study setting	Main findings
				H:Q ratios compared to athletes in other sports.
Enomoto et al. (2008)	Analytical cross-sectional	To examine the biomechanical characteristics of the running motion among top 3 placers during IAAF 100001m final.	Japan (Track-based)	The Kenyan (3rd placer) showed high stride frequency and small stride length (converse to the 1st placer). The Kenyan had greater thigh angles compared to the rest. There were minor changes in the minimum and maximum thigh and shank angles.

measurement tools and procedures. Two of these studies (Santos-Concenjero et al., 2016; Mooses et al., 2014) were descriptive cross-sectional studies with no comparison between Kenyan runners to other elite distance runners, while the other four studies (Sano et al, 2013, 2015; Kunimasa et al., 2014; Sano et al., 2013; and Lieberman et al., 2010) were descriptive analytical studies with a control group. Table 4 presents findings on anthropometric outcomes observed in the six reviewed studies.

3.2. Comparison of anthropometric outcomes

Table 5 illustrates the comparative values for means and standard deviations (SD) of the various anthropometric measures between elite Kenyan distance runners and controls in four reviewed studies. A meta-analysis of pooled data from three comparable descriptive analytical studies (Sano et al., 2015; Kunimasa et al., 2014; Sano et al., 2013) on gastroc-Achilles tendon length showed that elite Kenyan distance runners have significant longer gastroc-Achilles tendons than Japanese runners, while meta-analysis results on shank length showed no significant difference between elite Kenyan distance runners and Japanese runners. The high level of heterogeneity seen in these three pooled studies could be attributed to variations in instrumentation and data capture procedures (see Fig. 3).

3.3. Running gait biomechanics

Five studies (Santos-Concenjero et al., 2016; Sano et al., 2015; Lieberman et al., 2010; Enomoto et al., 2008; Kong and de Heer, 2008) analysed various aspects of running gait biomechanics. The main specific gait characteristics observed were; ground contact times, vertical ground reaction forces, foot strike patterns, stride length and stride frequency. All of the studies described use of valid and reliable measurement tools and procedures and findings indicate that elite Kenyan distance runners have 10% shorter ground contact times, greater torso forward lean and increased stride frequency and stride length relative to increased speed. The study by Lieberman et al. (2010) analysed foot strike patterns and ground reaction forces among habitually barefoot and shod Kenyan distance runners compared to American runners. It was observed that habitually Kenyan barefoot runners landed with fore foot or mid-foot strikes while shod runners were majorly rare foot strikers. Kinetic and kinematic analyses showed that even in hard surfaces, habitually Kenyan barefoot runners who fore-foot strike generated smaller collision forces than shod rear foot strikers.

A description of the study findings is presented in Table 6. A meta-analysis was not conducted because some outcomes were not investigated in more than one included studies or data were not reported.

3.4. Lower limb muscular factors

Two studies (Sano et al., 2015; Kong and de Heer, 2008) investigated lower limb muscle strength and soft tissue properties as possible determinants of running economy and performance. Both studies were conducted in a laboratory setting using validated and reliable tools and procedures by use of 3D motion capture and analysis and ultra-sonography. The factors which were studied were; stretch and shortening amplitudes of tibialis anterior, soleus and gastroc-nemius muscles, and the torque of quadriceps and hamstring muscles. The studies report that elite Kenyan distance runners have reduced Achilles tendon strain and gluteus medius muscle activation by allowing fascicles to work more isometrically during stance phase. The leg strength of elite Kenyan distance runners was relatively low compared to other athletes, although their Hamstring: Quadriceps ratio was high compared to athletes in other sports. Similarly, elite Kenyan distance runners demonstrated smaller stretching and shortening amplitudes of the gastrocnemius medialis and lower braking and pre-activation ratio of the gastrocnemius medialis and Achilles tendon. The shortening to stretching ratio of gluteus medius for elite Kenyan distance runners was smaller as well as a low muscle pre-activation ratio of gluteus

Table 3
Methodological quality assessment.

	STROBE checklist items																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	%
Santos-Concenjero et al., 2016	+	+	+	+	+	−	−	−	+	−	+	−	+	+	+	−	−	+	−	+	+	62
Sano et al., 2015	+	+	+	−	+	−	−	−	−	−	+	−	+	+	+	−	−	+	−	+	−	48
Mooses et al., 2014	+	+	+	+	+	+	−	−	+	−	+	−	+	+	+	−	−	+	+	+	+	71
Kunimasa et al., 2014	+	+	+	−	+	−	−	−	−	−	−	−	+	+	−	−	−	+	+	+	+	48
Sano et al., 2013	+	+	+	−	+	+	−	−	+	−	+	−	+	+	+	−	−	+	+	+	+	67
Lieberman et al., 2010	+	+	−	+	+	−	−	−	+	−	+	−	+	+	−	−	−	+	+	+	+	57
Enomoto et al., 2008	+	+	+	+	+	+	−	−	−	−	−	−	+	+	−	−	−	+	−	+	−	71
Kong and de Heer, 2008	+	+	+	−	+	−	−	−	+	−	+	−	+	+	+	−	−	+	+	+	+	57

Key: + Meets criteria, - Does not meet criteria.

Table 4
Anthropometrics.

Author (year)	Study outcome(s)	Measurement tools (reliability & validity)	Results	Interpretation
Santos-Concenjero et al. (2016)	Height (cm)	Stadiometer (Charder HM200P, Charder electronic company, Taiwan)	Height (cm) 170.5 (6.3)	Kenyan runners have low; body mass, BMI and total body fat composition, and their average height is high.
	Body mass (kg)	High precision balance (Seca 899, Seca, Germany)	Mass (kg) 54.8 (6.3)	
	BMI (kg m^{-2}) Body fat percentage	Skin fold callipers (Holitain Tanner-Whitehouse, Crymych, UK)	BMI 18.8 (1.3) $\sum$ 8 skin fold (mm) 34.2 (6.7)	
Sano et al. (2015)	Height (cm) Body mass (kg) Shank length (cm) Achilles tendon MA MG MTU Length (cm) MG tendinous tissue length (cm)	NR NR Ruler Ultrasound (13 MHZ, Prosound cv3, Hitachi Aloka Inc., Japan)	174.4 (7.9) 56.0 (7.1) 39.5 (3.0) 44.7 (4.6) 43.4 (3.5) 39.4 (3.3)	Height and body mass of Kenyan runners are similar to those of Japanese runners. Kenyan runners had significant longer; shank, Achilles tendon MA, MG muscle-tendon unit length and MG tendinous tissue length.
Mooses et al. (2014)	Height (m) Body mass (kg) BMI(kg m^{-2}) Achilles MA (cm) Shank length (cm)	Seca height rod 225, Seca GmbH & Co, Hamburg, Germany. Salter 144SVBKDR, Salter Houseware Ltd UK. Centurion Kit instrumentation (Rosscraft, Surrey, BC, Canada)	1.72 (0.07) 56.5 (5.7) 19.0 (1.3) 4.00 (0.43) 39.4 (2.4)	Kenyan runners have very low body mass and BMI. Achilles MA was strongly related with running economy. Leg length to body height ratio was related with performance.
Kunimasa et al. (2014)	Height (m) Body mass (kg) Body mass index (kg m^{-2}) Thigh length (mm) Shank length (mm) Gastrocnemius Achilles length (mm) Soleus Achilles length (mm) Achilles cross-sectional area (mm^2)	Ruler, Ultrasound analysis software (Image J, NIH, Bethesda, Maryland, USA) all measures were done according to the protocol described by Scholz et al.	1.74 (0.06) 57.2 (4.8) 18.9 (1.5) 426.5 (34.2) 397.4 (30.3) 262.7 (26.0) 72.3 (25.2) 60.5 (9.3)	The height, body mass and BMI of Kenyan runners were similar to Japanese runners. Kenyans have longer body segments at thigh, shank and foot, as well as greater absolute and relative values for Achilles tendon length (gastrocnemius and soleus) and Achilles cross-sectional area. Achilles MA showed positive correlation with endurance running performance.
Sano et al. (2013)	Height (m) Body mass (kg) BMI (kg m^{-2}) Shank length(m) Gastro Achilles tendon length (mm)	Ultrasonography using a linear array probe of 13 MHZ, Hitachi –Aloka Inc., Japan. Reliability of instrumentation has been reported previously	1.75 (0.06) 57.9 (5.1) 18.9 (1.5) 0.40 (0.02) 264.2 (24.5)	Height and shank length were similar between Kenyan runners and Caucasian controls. BMI for Kenyan runners was low but had longer Gastro Achilles tendon length.
Kong and de Heer (2008)	Height (m) Body mass (kg) BMI (kg m^{-2}) Leg length(m) Calf circumference (cm) Body fat (%)	Not reported	1.77 (0.06) 63.0 (7.3) 20.1 (1.8) 0.92 (0.06) 34.5 (2.3) 5.3 (1.6)	All anthropometric variables were within range reported in literature. Slender body type, low BMI and slim limbs

BMI Body mass index, MA $_{TA}$ Moment arm tendon Achilles, MG Gastrocnemius medialis, MG $_{MTU}$ Gastrocnemius medialis muscle-tendon unit, NR Not reported.

medius and Tibialis anterior. A meta-analysis was not conducted because there were no controls in the (Kong and de Heer, 2008) study, while in the Sano et al., 2015 study, values of the measurements were not reported. The reported findings for both studies are presented in Table 7.

3.5. *Biomechanical determinants of running economy and performance in distance running*

Fig. 4 illustrates comparable biomechanics of elite Kenyan distance runners in relation to a performance deterministic model established in literature (Saunders et al., 2004). Whereas the profile of elite Kenyan distance runners in particular anthropometrics, kinematics, kinetics and lower limb tissue characteristics highly resembles the proposed deterministic model of biomechanical factors for running economy and performance, it is imperative that considerations about the influence of these factors on RE and performance are made based on results of a significant meta-analysis.

Four studies (Sano et al 2013, 2015; Kunimasa et al., 2014; Sano et al., 2013; Lieberman et al., 2010) were analytical cross-sectional while the other four (Santos-Concenjero et al., 2016; Mooses et al., 2014; Enomoto et al., 2008; Kong and de Heer, 2008) were descriptive cross-sectional studies. All the eight reviewed studies were level V evidence. Following grading of evidence from all included studies, an algorithm (Fig. 5) was developed in order to provide a succinct synthesis of the current evidence base on biomechanical factors associated with running economy and performance of elite Kenyan distance runners.

Regarding consistency of evidence, anthropometric factors of reduced body mass, reduced BMI and increased average height were reported in six (Santos-Concenjero et al., 2016; Mooses et al., 2014, Sano et al, 2013, 2015; Kunimasa et al., 2014; Kong and de

Table 5
Comparison of biomechanical outcomes.

Author (year)	Outcome(s)	Sample(N)		Means (SD)	
		Kenyans	Controls	Kenyans	Controls
Sano et al. (2015)	Shank length (cm)	11	11	39.5 (3.0)	36.7 (1.8)
	Achilles tendon moment arm (mm)	11	11	44.7 (4.6)	37.0 (4.0)
	Gastroc-Achilles tendon length (cm)	11	11	39.4 (3.3)	35.3 (2.5)
Kunimasa et al. (2014)	Thigh length (mm)	22	22	426.5 (34.2)	398.2 (28.0)
	Shank length (cm)	22	22	39.7 (3.0)	36.5 (1.2)
	Gastroc-Achilles tendon length (mm)	22	22	262.7 (26.0)	224.7 (25.2)
	Achilles tendon cross-sectional area (mm^2)	22	22	60.5 (9.3)	53.6 (9.8)
Sano et al. (2013)	Shank length (cm)	10	10	40 (2.0)	43 (0.02)
	Gastroc-Achilles tendon length (mm)	10	10	394 (3.0)	353 (25)
Lieberman et al. (2010)	Ankle dorsi-flexion at foot contact (°)	14	8	−1.8 (74)	−28.3 (6.2)
	Knee flexion at foot contact	14	8	22.2 (4.3)	9.1 (6.4)

Heer, 2008) of the eight included studies. Increased shank length was reported in five studies (Mooses et al., 2014, Sano et al, 2013, 2015; Kunimasa et al., 2014; Kong and de Heer, 2008) while increased Achilles tendon length and Achilles tendon moment arm were reported in three (Kunimasa et al., 2014, Sano et al., 2013; Kong and de Heer, 2008) and two studies (Mooses et al., 2014; Sano et al., 2015) respectively.

Evidence on kinematics, kinetics, running gait cycle characteristics and lower limb tissue properties was not consistent across included studies as findings were not reported in more than one study apart from increase stride frequency which was reported in two studies (Enomoto et al., 2008; Kong and de Heer, 2008).

In this review, as illustrated in Fig. 5, biomechanical factors were considered to be associated with running economy and performance of elite Kenyan distance runners based on the level of evidence, consistency as well as whether evidence was based on significant findings of a meta-analysis of pooled homogenous studies. Therefore, according to this criterion, increased gastroc-Achilles tendon length **"is a factor"** associated with running economy and performance of elite Kenyan distance runners. Conversely, increased shank length **"is not a factor"** associated with running economy and performance of elite Kenyan distance runners, as pooled evidence from a meta-analysis indicated that there is no significant difference between the shank length of elite Kenyan runners compared to their counterparts. Meta-analysis of the other biomechanical factors was not performed as they were reported in not more than one included studies.

4. Discussion

Running economy (RE) is a complex multi-factorial measure of performance which reflects the combined functioning of biomechanical and neuro-muscular factors as well as metabolic and cardio-respiratory factors. Mitochondrial efficiency, Heart rate (HR), minute ventilation (V_E), thermoregulation (core temperature) (C_{Temp}) and muscle fibre type have been reported as the metabolic and cardio-respiratory pre-determinants of RE, however, there is no consensus on biomechanical determinants of RE.

This is the first systematic literature review to synthesize quantitative evidence on biomechanical factors for RE among elite Kenyan distance runners who are the world's best for the last four decades. We present quantitative evidence on eight level V studies (four analytical cross-sectional and four descriptive cross-sectional) all of which had moderate mean methodological quality score of 58%. The sample size of the included studies ranged from 3 (Enomoto et al., 2008) to 63 (Lieberman et al. study 2010).

Evidence base and consistency of anthropometric factors like reduced body mass, reduced BMI and increased average height was good across included studies since these factors were reported in six (Santos-Concenjero et al., 2016; Mooses et al., 2014, Sano et al, 2013, 2015; Kunimasa et al., 2014; Kong and de Heer, 2008) of the eight reviewed studies. Increased shank length was reported in five studies (Mooses et al., 2014, Sano et al, 2013, 2015; Kunimasa et al., 2014; Kong and de Heer, 2008), while increased Achilles tendon length and Achilles tendon moment arm were reported in three (Kunimasa et al., 2014, Sano et al., 2013; Kong and de Heer, 2008) and two studies (Mooses et al., 2014; Sano et al., 2015) respectively. Similarly, apart from increased stride frequency (Enomoto et al., 2008; Kong and de Heer, 2008), evidence on kinematics, kinetics, running gait cycle characteristics and lower limb tissue properties was not consistent.

The main finding of this review was that increased gastroc-Achilles tendon length **"is a factor"** associated with running economy and performance of elite Kenyan distance runners since the evidence was based on a significant meta-analysis on three homogenous analytical cross-sectional studies (Sano et al 2013, 2015; Kunimasa et al., 2014). Increased gastroc-Achilles tendon length among elite Kenyan endurance runners entails high levels of stored elastic and reduced amount of fatigue therefore contributing significantly to improved running RE and performance.

Study or Subgroup	Kenyans Mean	Kenyans SD	Kenyans Total	Controls Mean	Controls SD	Controls Total	Weight	Mean Difference IV, Fixed, 95% CI
Kunimasa et al 2014	39.7	3	22	36.5	1.2	22	37.1%	3.20 [1.85, 4.55]
Sano et al 2013	39.5	3	10	36.7	1.8	10	14.4%	2.80 [0.63, 4.97]
Sano et al 2015	40	2	11	43	0.02	11	48.5%	-3.00 [-4.18, -1.82]
Total (95% CI)			**43**			**43**	**100.0%**	**0.14 [-0.69, 0.96]**

Heterogeneity: $Chi^2 = 52.62$, df = 2 (P < 0.00001); $I^2 = 96\%$
Test for overall effect: Z = 0.33 (P = 0.74)

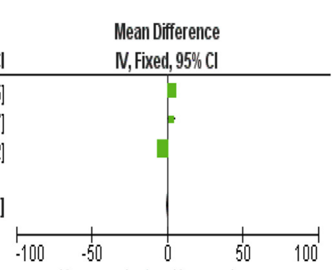

Fig. 3. Meta-analysis of shank length (cm).

Table 6
Running gait biomechanics.

Author (year)	Study outcome(s)	Measurement tools (reliability & validity)	Findings	Interpretation
Santos-Concenjero et al. (2016)	**Kinematics** Ground contact time (ms) Stride length(m) Stride frequency (m/s) Swing time(s) **Kinetics** Ground contact force Loading rate	VICON MX motion analysis system (Oxford metrics ltd, Oxford UK) in a 40m long indoor synthetic running track sampling at 250 HZ. 900 × 600 mm force platform (AMTI, Watertown, MA,USA) sampling at 2000HZ	0.18 (0.01)s Values on stride length, stride frequency, swing time and loading rate are not provided	Kenyan runners have 10% shorter ground contact times compared to those published in literature. However, stride length, swing time, stride frequency and ground contact time are not significantly associated with economical running.
Sano et al. (2015)	**Temporal spatials** Foot contact duration (ms) Braking time (ms) Push-off time (ms)	A video camera at 240 fps (HDR-CX550V, SONNY JAPAN) and marker points digitised by a software to calculate ankle and knee angles	205 (23) 108 (17) 97 (10)	Kenyan runners had significant smaller amplitudes of both knee and ankle flexions during braking phase and extension during push-off phase compared to Japanese runners.
Lieberman et al. (2010)	Foot strike pattern Vertical ground reaction force	3D Infrared kinematic system at 240 HZ and 500 HZ video camera (Fastec Inline 500M) and a 20–25m outdoor track of hard dirt using a 500-HZ video camera. GRF was recorded using AMTI force plates (BP400600 Biomechanics Force Platform).	Shod Kenyan runners are RFS while barefoot Kenyan runners are FFS. Barefoot RFS 1.89 (0.72) Shod RFS 1.74 (0.45) Barefoot FFS 0.58 (0.21)	Shod Kenyan runners were mainly rare foot strikers. Vertical GRF is 6.2% higher in shod runners who RFS than in barefoot runners who FFS at similar speeds
Enomoto et al. (2008)	Running velocity (m/s) Stride frequency (Hz) Step length (m)	Live videotaping of a race using digital Video cameras at 60 HZ	6.2 (m/s) 3.25 (Hz) 1.9 (m)	Kenyan runner showed high stride frequency and small stride length. The Kenyan's forward swing velocity of the thigh was low than that of the Ethiopian runner.
Kong and de Heer (2008)	Running speed (m/s) GRF (ms) Stride frequency (HZ) Ground contact time (ms)	8 camera motion capture system at 240 HZ. (VICON, Centennial, CO, USA)	4.5 (m/s) 191 (ms) 3.10(HZ) 184 (ms)	Kenyan runners have short ground contact times compared to those established among other elite runners. They also had increased stride frequency and stride length relative to increasing speed.

GRF Ground reaction force, FFS Forefoot strike, RFS Rare foot strike.

On the other hand, increased shank length **"is not a factor"** associated with running economy and performance of elite Kenyan distance runners, as pooled evidence from a significant meta-analysis indicated that there is no significant difference between elite Kenyan runners compared to their counterparts.

On the other hand, there is significant evidence base as well as consistency of findings on elite Kenyan distance runners regarding slender and tall body type, low BMI, low body mass, slender and long lower limbs with mass distributed more proximally, longer Achilles tendon tissue and Achilles moment arm as well as lower foot levers. According to the findings of our review, these **"maybe factors"** associated with performance of elite Kenyan distance runners although we could not make conclusive recommendations with certainty of evidence since a meta-analysis was not possible.

Another biomechanical factor which is purported to influence the extra-ordinary performance of elite Kenyan distance runners is shorter ground contact and flight times and small ground reaction forces during the running gait cycle compared to established times on other distance runners (Lieberman et al., 2010). Similarly we could not make any recommendation with certainty of evidence for

Table 7
Lower limb muscular factors.

Author (year)	Study outcome(s)	Measurement tools (reliability & validity)	Findings	Interpretation
Sano et al. (2015)	Stretch amplitude (aEMG) Shortening amplitudes (aEMG) (Tibialis anterior, Soleus and Gastrocnemius medialis)	Bipolar surface electrodes, parallel bar electrodes size 2 mm × 9 mm (NM-512G, Nihon Koden, Japan) and a multi-telemeter AD converter system (WEB-5000, NIHON KODEN, Japan)	3.0_{Fa} 5.8_{Fa}	Kenyan and Japanese runners presented similar EMG patterns for soleus muscle, while tibialis anterior and gastrocnemius medialis EMGs were lower in Kenyan runners during pre-activation and braking phases.
Kong and de Heer (2008)	Quadriceps isometric torque (Nm/kg) Hamstring isometric torque (Nm/kg)	Isokinetic dynamometer (System 3 pro, Biodex medical system, NY, USA)	40° knee flexion = 1.50, 50° knee flexion = 1.75, 60° knee flexion = 2.00, 70° knee flexion = 2.25, 80° knee flexion = 2.50 and 90° knee flexion = 2.50	Quadriceps torque increased with muscle length peaking at 80° to 90° knee flexion. Hamstring torque peaked as the muscle was shortening. H:Q ratio increased as the angular velocity increased.

EMG electromyography.

Table 8
NHMRC grading of evidence for aetiological factors.

Evidence level	Study design
I.	Systematic review of prospective cohort studies
II.	One prospective cohort study
III.	One retrospective cohort study
IV.	A case control study
V.	A cross-sectional study or case series

or against because a meta-analysis was not possible and the results are based on one descriptive analytical study with questionable methodology because data from the case group (Kenyan runners) was collected on an out-door track experiment while the control group were analysed in an in-door laboratory set up with variations in instrumentation which is a likely source of bias.

Other notions which could not be confirmed through a meta-analysis even though they can be theoretically linked to reduced fatigability and improved endurance is that elite Kenyan distance runners utilise effective exploitation of stored elastic energy through greater shortening to stretching ratio of lower limb muscles and increased quadriceps and hamstring torque (Santos-Concenjero et al., 2016).

Therefore, while RE is a known determinant of distance running performance which is influenced by complex multiple factors, and the general consensus on some metabolic and cardio-respiratory determinants of RE including, HR, V_E and C_{Temp} among endurance athletes (Saunders et al., 2004), the association between these factors and performance of elite Kenyan distance runners can only be confirmed through a systematic review of high quality prospective cohort studies. Otherwise, the extra-ordinary dominance of Kenyan distance runners in global competitions shall continue to remain a paradox to scientists, coaches as well as competing athletes. Similarly, high quality prospective cohort studies are desirable to establish significant evidence base for biomechanical as well as neuro-muscular determinants of RE and performance other than increased gastroc-Achilles tendon length which has been identified in this review.

4.1. Review limitations

This review only considered studies published in English language. We included a relatively low number of studies (8) based on the inclusion and exclusion criteria and the mean methodological quality score of all included studies was moderate. Similarly, the level of evidence for all included studies was very low hence

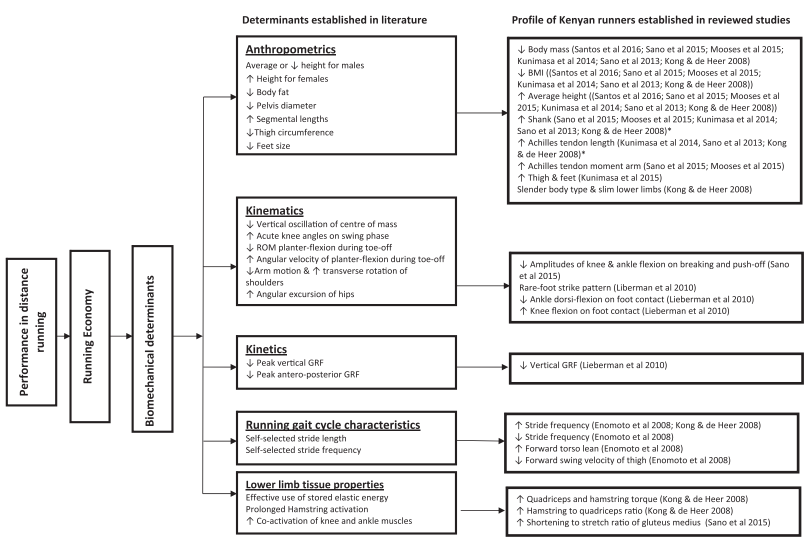

Fig. 4. Biomechanical determinants of running economy and performance in distance running.

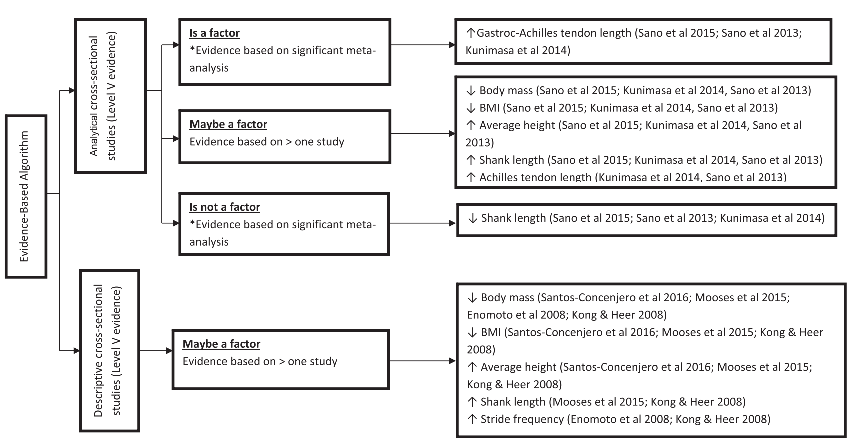

Fig. 5. Algorithm of evidence-based biomechanical factors associated with running economy and performance of elite Kenyan distance runners.

impacting on the level of certainty of the evidence. Also, there were differences in instrumentation in one of the reviewed studies which presents a possible source of bias hence impacting on the quality and strength of evidence.

5. Conclusion

Kenyan distance runners have significant longer gastroc-Achilles tendons compared to other elite distance runners. There is no certainty of evidence on the association between RE and their slender and tall body type, low BMI, low body mass, slender and long lower limbs, proximally distributed lower limb mass, longer Achilles tendon, longer Achilles moment arm and lower foot levers. To allow for a better understanding of the running biomechanics of the elite Kenyan distance runners, future primary research should focus on the other performance determinant factors like vertical oscillation of the centre of mass, upper limb motion and anterior-posterior ground reaction forces which are included in the performance deterministic model but have not been empirically investigated on the elite Kenyan distance runners.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The secondary data sets generated and analysed in this review are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interest.

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Authors' contributions

NT and QL developed the review protocol. NT conducted search process and data extraction. Both authors did quality appraisal of included studies and evidence synthesis as well as writing, reading and approving the final draft manuscript.

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Abbreviations

GRF	Ground Reaction Forces
AT_{MA}	Achilles tendon moment arm
EMG	Electro-myography
ROM	Range of Motion
BMI	Body Mass Index
CoM	Centre of Mass
Vo2	Maximal oxygen consumption
MG	Gastrocnemius medialis
V_E	Minute ventilation
HR	Heart rate
C_{Temp}	Thermoregulation core temperature

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