Review Paper

Does step frequency as a single factor affect running economy? A systematic review

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ABSTRACT

Is step frequency (SF) related to running economy and how? This is the main question we have tried to answer in this study. It is a well-known biomechanical variable used in scientific and practical analysis of running technique. A systematic review was carried out to analyse available literature of the field. Scopus, Web of Science and ScienceDirect databases were used for article search. In total 249 articles matched defined queries and after exclusion, 12 were used in the review. After analysis of the review, our hypothesis remained unconfirmed. In some cases, step frequency affected the running economy, while in others it did not have a direct impact on it. It might be that SF cannot be considered in isolation from other biomechanical characteristics and it cannot be analysed as a universal criterion for improving running technique and economy.

Keywords: Running, Biomechanics, Running economy, Step frequency, Cadence.

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INTRODUCTION

Step frequency (SF) in running seems to be an easily understandable and applicable biomechanical variable. With a growing number of available smart technologies in everyday life and sports monitoring, SF has become an easily measurable and popular variable to analyse (Borowski-Beszta and Polasik, 2020; Rodgers et al., 2014). Athletes and coaches are using different tools to estimate and analyse their SF in training and competitive running. Not only for measuring it but also correcting, training, and im- proving (Quinn et al., 2021). This raises many questions on how to correctly interpret this variable. What is the "*correct*" or "*optimal*" step frequency in distance running? Is there an optimal SF for everyone? Is optimal also the one which we prefer? And more.

Running velocity is determined by SF and step length. Changing one or both parameters can lead to a change in running velocity. In this case, researchers often talk about average running velocity, which is a product of average SF and step length. It can also be described as an average distance travelled per cycle of movement and the average frequency at which the cycle of movement is repeated. This makes SF as the very basic foundation of the running cycle (Hay, 2002).

A different terminology might be used in reporting the SF values. Frequency, rate, cadence, and tempo are the most popular mentioned in research papers but often report the same thing. In this article "*step frequency*" is used in all cases. Also, some studies report "*step*" frequency and others "*stride*" frequency. Step length is the horizontal distance between the point of touchdown of one foot to the following touchdown of the opposite foot. Stride length is the horizontal distance between the point of touchdown of one foot to the following touchdown of the same foot. The average stride frequency is two times greater than the step length. SF can be measured as steps taken per second or per minute. In sprint running it is more important to measure steps taken every second. In long-distance running, it is more often to report steps taken per minute. Also, it is a more understandable way of reporting these values to practitioners. Smart technologies in sports coaching also use this way of reporting SF more often. Frequencies can be reported in steps or strides as well.

One of the biggest benefits of measuring SF and length is the ability to compare it between left and right foot data. Different technologies can be used to measure SF and length: video analysis (Hunter et al., 2004), optical systems (Santos-Concejero et al., 2014), smart socks (Oks et al., 2017), accelerometers (Rowlands et al., 2007), and others. Sometimes in biomechanics, different methods introduce different errors which need to be addressed properly (Abolins et al., 2019; Metcalf et al., 2014).

In cyclic activities or locomotion, the average speed is determined by the average distance covered per cycle of motion and the average frequency at which the cycle of motion is repeated. To gain or reduce running velocity a runner can freely increase or decrease its step length or frequency. Both variables are highly correlated with velocity, but they might be independent of each other (Hunter et al., 2004).

In continuous human movements, the frequencies usually are self-selected and described as the preferred step frequency (PSF) in running (Heiderscheit et al., 2011). A person can walk or run without thinking about their step frequency and feel comfortable with it. The PSF has been reported to be close to optimal in trained runners (De Ruiter et al., 2020). Meaning that it is optimal regarding metabolic energy expenditure. PSF or length is also used to normalize SF values between research subjects. Individual approach in normalizing SF in research plays an important role. It cannot be normalized by the runner's qualification, not even by body or leg length (Brisswalter et al., 1996).

Preferred SF does not necessarily mean optimal. Sometimes SF has a U-shaped relationship with metabolic energy expenditure. Energy expenditure rises with both - increased and decreased SF. In long-distance running, optimality is connected to running economy (RE). Running economy is a multifactorial component determining humans' ability to reduce the metabolic cost of running (Williams and Cavanagh, 1987). It can also be defined as steady-state oxygen consumption at a certain running velocity (Foster and Lucia, 2007). It is linked to running performance and runners with a higher RE tend to run faster at longer distances (Folland et al., 2017). RE is affected by different groups of variables: physiological, neuromuscular, biomechanical, and others (Barnes and Kilding, 2015). Every biomechanical variable contributes to the total energy expenditure of running and plays a role in the RE. Biomechanical variables like SF can be analysed as multiple factors and as single ones (Moore, 2016).

Some studies report that experienced runners have an optimal step frequency of close to 180 steps (90 strides) per minute (Cavanagh and Williams, 1982; Kaneko et al., 1987), and when freely selecting SF, they select it within 3% of optimal values (Pate et al., 1987).

RE is mostly studied with shod runners, however, there are multiple studies looking at RE in barefoot running. Studies show that running barefoot increases SF (Bonacci et al., 2013; De Wit et al., 2000; Divert et al., 2005) and it affects RE too (Hanson et al., 2011). In our study, we didn't have criteria for running footwear, because, in our systematic review, SF was analysed as a single factor that affects RE. However, RE was not pre-defined.

RE is measured by combining the biomechanical and physiological characteristics of running. Different physiological characteristics can be used to assess the running economy. The most used is oxygen consumption. Heart rate can be used too, both alone and in combination with oxygen consumption characteristics. Lactate concentration characteristics can also be used but cannot be measured continuously.

To assess changes in the running economy, it is necessary to change the biomechanical parameters and monitor the effect on physiological parameters.

Before embarking on the systematic literature review study, it was hypothesized: If indeed, SF affects RE, then by changing SF (increasing or decreasing), RE will be affected negatively (our hypothesis).

METHODS

In this section, the methodology of this systematic review is described (see the flow diagram in Figure 1 for an overview). The whole process consisted of four phases: identification, screening, eligibility, and included.

Identification

To identify the articles with the potential to be included in the review, on the 8th of July 2022 a search was conducted in three databases containing peer-reviewed articles: Scopus, Web of Science, and ScienceDirect. The queries used and related results are shown in Table 1. In Scopus 206 articles were found, while in Web of Science 139 and in ScienceDirect 21 articles, resulting in a total of 366 articles. After removing duplicates 249 unique articles were left for the next step.

All searches were performed in these fields: Title, Abstract, and Keywords.

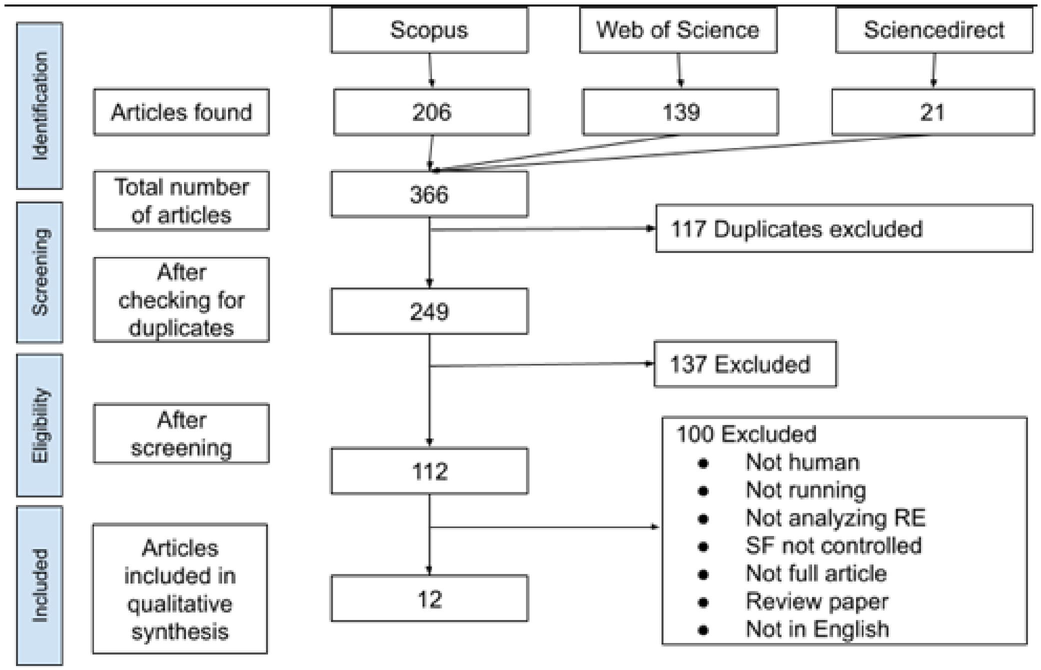

Figure 1. Flow diagram overview of the systematic review methodology and results at each stage.

Table 1. Databases and queries used for identification and the number of resulting articles.

Database	**Query**	**Results**
Scopus	TITLE-ABS-KEY (running AND (” step frequency” OR” step rate” OR” stride frequency” OR ”stride rate”) AND (economy OR optimal OR efficiency OR efficient))	206
Web of Science	((TI=((running AND (”step frequency” OR ”step rate” OR ”stride frequency” OR ”stride rate”) AND (economy OR optimal OR efficiency OR efficient)))) OR AB=((running AND (”step frequency” OR ”step rate” OR ”stride frequency” OR ”stride rate”) AND (economy OR optimal OR efficiency OR efficient)))) OR AK=((running AND (”step frequency” OR ”step rate” OR ”stride frequency” OR ”stride rate”) AND (economy OR optimal OR efficiency OR efficient)))	139
ScienceDirect	Title, abstract, keywords: (running AND (” step frequency” OR” step rate” OR” stride frequency” OR” stride rate”) AND (economy OR optimal OR efficiency OR efficient))	21
Total		**366**

Screening

After identification, duplicates were removed leaving only unique articles. The remaining number of articles were examined by reading the title and abstract. All authors were involved in the screening phase, each examining a random subset of articles. The screening criteria for inclusion were:

- The article is in English.
- Measured running step (stride) rate or frequency.
- Measured RE.
- Subjects are humans.

Eligibility

All the articles left after screening were tested for eligibility by examining their full text. All authors were involved in the eligibility phase, each examining a random 4 subset of articles. The eligibility criteria for inclusion were:

- Article full text is available - among search results, some publications were only abstracts or their full text was otherwise unavailable - such articles were not eligible.
- Article is an experimental study (not a review).
- Article is in English.
- Measured running step (stride) rate or frequency.
- Measured RE.
- Controlled SF.
- Compared if SF affects RE or vice versa.
- Subjects are humans.

Included

After eligibility criteria were applied, the remaining unique articles were included for the data extraction of the following parameters:

- Information about subjects - count, sex, qualification.
- Running surface.
- The inclination of the running surface.
- Criteria for RE.
- Running speed.
- Step frequency.
- Main conclusion.

If any of the extractable parameters were not mentioned in the article, they were marked as "*not reported*". Each author extracted parameters from a randomly assigned set of articles.

RESULTS

In total 249 articles were identified and screened. After screening, 137 articles were excluded, and 112 articles were used to check eligibility from which 12 articles were selected for further analysis (see Table 2). From these articles, 9 parameters (number of subjects, sex, qualification, running surface, inclination, criteria of RE, running speed, SF, main conclusion) were extracted that described research methods and main results. In 6 out of 12 articles only males were analysed but in 5 articles both male and female subjects participated in the study. However, one article studied only females. On average 12.75 ± 4.83 subjects participated in the study ranging from 6 subjects up to 22, but in most of the studies, the number of subjects was below 16.

In all studies except one, experienced or recreational runners were recruited. In one study inexperienced runners were recruited. In all studies, the experiment was performed on a treadmill. The inclination of the treadmill mostly was not specified (6 articles) or 0% (4 articles). In 1 one study, it was ± 3%, and in one it was 0% and -6%. The running speed was varying a lot and was between 10.08 to 18.4 km/h. The step frequencies were varying between 75% to 118% of the PSF. Most often the step frequency was set to ± 4, 5, or 10% from PSF.

Oxygen required in steady state (VO_2) was used in most studies (8 articles) as the main criteria for RE. Oxygen cost of running per distance as the main criteria were used in 2 articles, and metabolic cost in 2 articles.

One study showed the highest running economy when running with a preferred stride length and quadratic fit showed that RE could be optimized at a 2.9% shorter stride than preferred (Connick and Li, 2014). However, the only stride length with significantly lower RE was the longest (+8% from preferred). This study varied SF to change stride length, and they did not analyse SF's impact on RE. In another study, a greater RE was observed when running at 95% of PSF compared to 105% of PSF. However, there were no other significant differences in RE between SF (Lim et al., 2020).

Lieberman with his team showed that when running 3 m/s (10.8 km/h) the optimal SF is 85 strides per minute (Lieberman et al., 2015). Their difference between predicted and measured optimal SF was within 2 strides per minute. They also showed that metabolic cost increases deviating from optimal SF.
In a study where runners were tested on different slopes and SFs, the authors didn't find any significant differences between optimal SF and preferred SF. However, by changing SF all subjects increased their metabolic cost by 9 - 21%, depending on the slope and SF (Snyder and Farley, 2011). Like Snyder and Farley, Vernillo with his team didn't find any significant differences between preferred and optimal stride frequencies (Vernillo et al., 2019). By lowering SF to 92% of PSF runners increased their metabolic cost by about 8.5% and by increasing SF to 108% of PSF they increased metabolic cost by about 6.5% (Vernillo et al., 2019), however, Hafer showed in a pilot study of 6 subjects that increasing cadence by 10% do not change running efficiency (Hafer et al., 2015).

Hunter and Smith also didn't find any significant differences between preferred and optimal stride frequencies (Hunter and Smith, 2007). They also didn't find an association between changes in VO_2 and SF. de Ruiter in a study compared PSF with OSF. The results showed no significant changes in running cost when changing SF from preferred to optimal, however, the study showed that all novice runners preferred lower SF than OSF, and 3 subjects reduced their running cost by 3-5%. But as mentioned before other subjects didn't have such a reduction in running cost (De Ruiter et al., 2014).

Mercer in a study got mixed results. VO_2 tended to differ between SF (with p = .059). It was significantly different only at some speeds and some SF - VO_2 was lower when running with speeds 3.13 m/s and 3.58 m/s and with 15% lower SF than PSF, however, it was not different at other speeds and SFs (Mercer et al., 2008).

In a study where running cadence was decreased by 10% from freely chosen cadence, researchers didn't find any significant difference in VO_2 (Billat et al., 1999). Similar results were found in a study where, in contrast to the previously mentioned study, the frequency was increased by 10% (not decreased). The researchers concluded that by increasing SF for inexperienced runners RE does not change (Dewolf et al., 2022).

Another study showed that a short period of increased step frequency training (10 days) can lower oxygen consumption by 11%, increase step frequency by 7%, and shorten step length by 3.7% (Quinn et al., 2021). However, this study didn't look at the optimal step frequencies and didn't compare if the subjects were close to the OSF before the experiment or not.

Table 2. Extracted data from identified and screened articles.

Article	**Subjects**	**Sex**	**Qualification**	**Running surface**	**Inclination**	**Criteria for RE**	**Running speed (km/h)**	**SF (% from preferred)**	**SF effect on RE**
(Connick and Li, 2014)	11	M	Runners (long distance)	Treadmill	0%	Steady-state oxygen required	13	92, 96, 100, 104, 108	OSF is 2.7% shorter than PSF
(Lim et al., 2020)	12	M	Runners (recreational)	Treadmill	0%	Steady-state oxygen required	Constant	90, 95, 100, 105, 110	Only difference was observed between 95% and 105% of PSF
(Lieberman et al., 2015)	12+2	M/F	Runners (recreational)	Treadmill	-	Oxygen cost of running per distance	10.8	75, 80, 85, 90, 95	Optimal SF is 85 strides/min
(Snyder and Farley, 2011)	9	M	Runners (recreational)	Treadmill	±3deg	Metabolic cost	10.08	85, 92, 100, 108, 115	No difference between OSF and PSF
(Vernillo et al., 2019)	15	M	Runners	Treadmill	-	Metabolic cost	10.8	92, 96, 100, 104, 108	No difference between OSF and PSF
(Hafer et al., 2015)	2+4	M/F	Runners (recreational)	Treadmill	-	Steady-state oxygen required	Preferred	100, 110	Increased cadence (+10%) doesn't affect RE
(Hunter and Smith, 2007)	11+5	M/F	Runners (experienced)	Treadmill	-	Steady-state oxygen required	96-99% of 10km race pace	92, 96, 100, 104, 108	No difference between OSF and PSF. No association between VO2 and SF
(De Ruiter et al., 2014)	10+10	M	Runners	Treadmill	0%	Oxygen cost of running per distance	Speed of 80% individual ventilatory threshold	82, 88, 94, 100, 106, 112, 118	No difference between OSF and PSF
(Mercer et al., 2008)	4+6	M/F	Runners	Treadmill	-	Steady-state oxygen required	11.3, 12.9, 14.5	85, 100, 115	Mixed results. SF affects RE in some speeds
(Billat et al., 1999)	8	M	Triathletes (well trained)	Treadmill	0%	Steady-state oxygen required	18.4 ± 1.1	90, 100	Decreased cadence (-10%) doesn't change VO2
(Dewolf et al., 2022)	8+2	M/F	Inexperienced runners	Treadmill	0%, -6%	Steady-state oxygen required	10.76 ± 0.65	100, 110	Increased cadence (+10\%) doesn't change RE
(Quinn et al., 2021)	22	F	Runners (long distance)	Treadmill	-	Steady-state oxygen required	12.24 - 13.68	180 b/min	Increased SF training improved RE

Note. Steady-state oxygen required is measured in $ml\cdot kg^{-1}min^{-1}$; Metabolic cost is measured in $J\cdot kg^{-1}m^{-1}$; Oxygen cost of running per distance is measured in $ml\cdot kg^{-1}km^{-1}$. RE - running economy, SF - step frequency, PSF - preferred step frequency, OSF - optimal step frequency.

DISCUSSION

Step frequency is a fundamental biomechanical characteristic of running that is relevant to both sprint and long-distance running. In long-distance running, it is important not only to analyse the biomechanical characteristics per se but also to combine them with physiological parameters and to evaluate them in the context of running economy. Despite this, we were unable to find many studies that investigated the direct relationship to the running economy and how it is affected by SF performance. Why so? It is difficult to give a clear answer to this question. Modern laboratory equipment makes it easy to measure this biomechanical parameter. It is possible to obtain applicably representative datasets for each runner under many different running conditions. However, in most running biomechanics studies, SF data are analysed more as "*background*" data while measuring other, more complex parameters. It would be hard to believe that SF has no effect on running economy, which is closely related to performance in long-distance running. SF is a relatively easy metric to manipulate. Also frequently used in the training process for long distance runners.

We came across different methodological choices that researchers make in their research - definition of running speed, the choice of surface slope, and the criteria for normalizing running stride frequency. These are all fundamental principles for studying the effects of changes in SF under different conditions and its relationship with the economy.

Also, various terminological nuances - how to name stride frequency. Frequency, pace, cadence - these all are discussed. We included all these in our literature search. However, we do not see a problem that the use of different terminology would in any way affect the quality of the research. This is probably not only a biomechanical discussion but also a linguistic one. Although researchers do not disagree on what SF is in essence, different terminology is accepted to describe it.

It is very common in running studies to collect SF data and analyse it even if it is not the main object of the study (Gil-Calvo et al., 2020; Oks et al., 2017). In our review, in multiple studies, SF is examined and even the relationship with RE is analysed. However, SF is not always controlled (Barnes et al., 2014; Concejero et al., 2014; Gómez-Molina et al., 2018; Halvorsen et al., 2012; Santos-Concejero et al., 2013, 2015, 2017; Tartaruga et al., 2012). This shows that SF and RE relationship is not completely understood. Studying SF and RE relationship without controlling SF, one can't tell if the RE is affected by SF.

It is important to note that RE is not always measured with the same methods. Running economy can be measured using different physiological and biomechanical parameters. It is not certain that all physiological measures can be interpreted in the same way in the context of a running economy, so it is important for studies to define exactly how this has been done. This should also be considered when comparing the results of different studies.

Reviewed articles show that there isn't a significant difference between PSF and OSF. Even if there is a numerical difference between these two values. Usually it is so low, that changing SF from preferred to optimal does not change the running economy. However, deviating from PSF or OSF too much, lowers RE. This phenomenon was observed in all studies.

Studies show mixed results in the relationship between SF and RE. Some studies show that lower SF improves RE, some show that higher SF is better, but some show no significant difference in RE when changing SF. Of course, we are talking about proportionate changes in these cases. Huge changes in SF will cause huge changes in the energy expenditure as well. This doesn't give a clear answer to the question - does SF affect RE? In a specific way and as single factor, of course.

It is difficult to compare the change in the running economy, while analysing the SF deviations from the PSF. It is mainly because the authors use different limits of change. Also, different limits of change are allowed at different running speeds. It is also not always known how relatively difficult this is for everyone. Even if we know this, it is still open to criticism as a factor in the standardization of exercise. In this type of study, a choice will always have to be made, whether to standardize exercise load relatively or to standardize everyone at the same running speed, which does not produce the same exercise effects for everyone.

Our hypothesis has not been confirmed. In some studies, SF affected RE while in others it didn't. In those where it affected RE, it affected sometimes negatively, but sometimes positively.

CONCLUSION

There is no doubt that SF plays a big role as a fundamental biomechanical indicator of running. It is an important tool to monitor the technical performance of running. However, research shows that it rarely correlates with the running economy as a separate variable. It is important to note here that this study only looked at SF as a separate, individual measure and sought to correlate it with the economy. The lack of significant evidence for this link is open to debate. Perhaps the key lies in the fact that this indicator cannot be considered in isolation from other biomechanical characteristics. Maybe the answer is by using a different, interdisciplinary approach. In the introduction of the article, it was already pointed out that SF parameters are analysed to control, improve, and train them. But the findings of this study show that perhaps this parameter cannot be considered in isolation and analysed as a universal criterion for improving running technique and economy.

AUTHOR CONTRIBUTIONS

E. Bernans: designed the study; wrote the paper; data interpretation. V. Abolins: designed the study; wrote the paper; data collection, analysis, and interpretation. J. Lanka: designed the study; data interpretation; supervision.

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DISCLOSURE STATEMENT

No potential conflict of interest were reported by the authors.

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