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Resonance in Human Walking Economy: How Natural Is It?

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Resonance in Human Walking Economy: How Natural Is It?

Peer Review
This work has undergone a double-blind review by a minimum of two faculty members from institutions of higher learning from around the world. The faculty reviewers have expertise in disciplines closely related to those represented by this work. If possible, the work was also reviewed by undergraduates in collaboration with the faculty reviewers.

Abstract
Locomotion and movement economy are cornerstone topics in movement science. Modeling the leg as a hybrid mass-spring pendulum shows walking economy should be optimized when stride frequency matches the resonant frequency of the limb. Human walking is described as self-optimizing because mean preferred (PSF) and modeled resonant (RSF) stride frequencies usually are statistically equivalent, but this depiction may not be fully justified. **Purpose:** To more thoroughly examine the self-optimization characterization and the consequences of obligating use of the RSF. **Methods**: Forty-seven individuals of diverse statures completed 3 consecutive days of preferred walking trials on a treadmill where stride rate, stride length, walking speed, heart rate and walking economy measures were made under steady state heart rate conditions. Anthropometric measures were taken to build a hybrid model of the leg and model the RSF. Reliability across days was evaluated via repeated measures analysis of variance (ANOVA) and intra-class correlation (α=.05) and correlations were calculated for PSF and RSF. A separate sample of 20 participants walked under 3 conditions, (1) completely preferred; (2) at the original preferred speed using the RSF; and (3) with the option to establish a new preferred speed while using the RSF. **Results**: Gait characteristics were fundamentally reliable across days and the correlation between PSF and RSF was weak (8% explained variance). Walking economy improved 14% when using the RSF and allowed to self-select the speed / stride length used at that cadence. **Conclusions**: The results raised slight questions about current self-optimization presumptions and further emphasized the role of resonance in walking economy

Keywords
gait, self-optimization, resonance

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INTRODUCTION

The issues surrounding movement efficiency and economy are fundamental to our understanding of animal movement processes and intuitively appealing problems to novice and expert investigators alike. Economy may be defined as obtaining task goals effectively and proficiently with a minimum of effort (Sparrow & Newell, 1998). While this is a holistic conceptual approach, such a perspective has proven useful for a wide variety of important questions in biology and its associated disciplines (Full, 1991). Optimization of biological processes and functions, like gait, may have great adaptive significance (Steudel-Numbers & Tilkens, 2004).

The gait behavior of animals, including humans, generally has been characterized as self-optimizing. Support of this natural inclination for economy arises from many studies reporting that use of the preferred, or self-selected, gait speed allows for a favorable balance of physiologic cost (based on both indirect and direct measures) and functional output. Emphasizing humans, preferred speeds reportedly incur lowest ratings of perceived exertion (Messier, Franke, & Rejeski, 1986), rates of energy expenditure in walking (Holt, Hamill, & Andres, 1991) and running (Hamill, Derrick, & Holt, 1995) and overall cost of transport (Saibene & Minetti, 2003). Observed cost of transport is also minimized at preferred speeds for other animals including bipeds (Watson et al., 2011) and quadrupeds (Langman et al., 1995; Wickler, Hoy, Cogger, & Hirschbein, 2000). What is the mechanism for optimizing gait economy?

Basic mechanical models that simplify the complexity of functional movement, yet accurately preserve and reflect the organism's behavior, can be very helpful. The pendulum-like features of many forms of animal transport have long been recognized and have led to several different types of pendulum models applied to the study of terrestrial gait. A compelling case has been made for a pendulum-based mechanism that leads to optimal walking economy. For an organism, the energy conservation assumptions of idealized pendulum models are not met; Cavanagh, Saibene, and Margaris (1976) showed energy exchange in human walking to be about 60%. Thus, muscle must utilize metabolic energy to provide periodic inputs of force necessary to maintain oscillation (i.e., striding). In principle, it is known exactly how to minimize the force needed to maintain oscillations. If the force pulse is applied on a schedule that matches the natural, or resonant, frequency of the pendulum, the amount needed is minimized. We know this intuitively from pushing a child on a swing; we naturally push only at the top of the backswing, timing our force input to the natural frequency of the swing/child pendulum. Providing these pulses on the resonant frequency schedule should minimize the muscle force needed and the associated metabolic cost; thus, to optimize walking economy, a stride frequency that matches the resonant frequency of the leg-pendulum should be used (Doke, Donelan, & Kuo, 2005; Holt, Hamill, & Andres, 1990; Lin-Chan, Nielsen, Yack, Hsu, & Schurr, 2003).

The resonant frequency is determined by the fundamental physical characteristics of the leg and energy conservation effects from gravitational and elastic influences. Obusek, Holt, and Rosenstein (1995) provide a nicely detailed overview of a force-driven, hybrid mass-spring pendulum model of the walking human leg used in many studies (Decker, Torry, Noonan, Sterett, & Steadman, 2004; Hamill, Derrick, & Holt, 1995; Holt, Hamill, & Andres, 1990; Holt, Hamill, & Andres, 1991; Holt, Jeng, & Fetters, 1991; Holt, Saltzman, Ho, & Ulrich, 2007; Schot & Decker, 1998). The resonant stride frequency equation for a physical pendulum shown below is equivalent mathematically to this hybrid pendulum model version:

$$RSF\ (Hz) = 1 / [2\pi\{MOI/(mdgc)\}^{1/2}]$$

where:

RSF refers to the resonant stride frequency,
MOI refers to the moment of inertia of the whole leg about the hip,
m represents the mass of the whole leg,
d represents the distance from the hip joint to the whole leg center of mass,
g is gravitational acceleration, and
c represents a gravitational and elastic energy conservation ratio modulated by muscular stiffness (2.0 for normal, mature walking as per Obusek, Holt, & Rosenstein, 1995).

Values for the *MOI*, *d* and *m* terms are calculated from measures made on each subject and combined with standard anthropometric estimates.

It also has been reported that the resonant stride frequency for this model demonstrates good agreement with the preferred stride frequency (PSF) seen for human walking. This includes adults walking forward normally and when wearing ankle weights to experimentally lengthen the leg-pendulum (Holt, Hamill, & Andres, 1990) and also backwards (Schot & Decker, 1998). There is also a developmental or learning aspect apparent in this dynamic; early walkers tend not to demonstrate this (Holt, Saltzman, Ho, & Ulrich, 2007) while 9-year-old children do (Holt, Jeng, & Fetters, 1991). These findings, when considered with the previously cited studies of physiological cost at preferred gait speeds reveal a clean logical series; preferred speed gait seems to minimize costs and the stride frequency used at this speed seems to match with the resonant (stride) frequency (RSF) for a hybrid pendulum-leg model. Thus, resonance seems to be a natural, key mechanism in walking economy.

If applied at a high level of analysis (e.g., across species), the evidence for self-optimization through a resonance mechanism appears strong (Turvey, Schmidt, Rosenblum, & Kugler, 1988). However, conclusions that humans are self-optimizing based on studies composed of fairly small and homogenous samples, or when the resonance concept is introduced to clinical and/or developmental settings (Decker, Torry, Noonan, Sterett, & Steadman, 2004; Holt, Saltzman, Ho, & Ulrich, 2007), suggest that this mechanism is or should be the dominant response by most individuals, too. It is entirely possible that some other functional priority is emphasized (e.g., stability) by various individuals, depending on their current psychological or physiological states. Observing no significant difference between mean RSF and PSF generally is taken as an indication that individual stride frequencies were indeed predicted by the model (Holt, Hamill, & Andres, 1990; Holt, Jeng, & Fetters, 1991b; Obusek, Holt, & Rosenstein, 1995; Schot & Decker, 1998), but this conclusion may not be fully warranted. This result also could occur when very few, if any, individuals in the sample actually demonstrate behaviors near the mean, an outcome that occurs frequently in human movement (Bates, 1996; James & Bates, 1997). To develop a more complete picture of individual human gait economy dynamics, correlation-based analyses should be included, as has long been done in investigations of general laws of locomotion that include multi-species samples (Alexander, 2004; Taylor, Hegland, & Maloiy, 1982).

Information in two studies reporting RSF and PSF equivalence allowed for a re-examination via correlation; the coefficients

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for these were weak to non-existent which speaks directly to the concerns raised here. It must also be recognized that if a good portion of a homogenous sample (which is likely the case with most studies in this area) was operating near resonance, the correlation coefficient could be very weak. We suggest that focusing recruitment to achieve a wide range of statures and then applying correlation analyses would offer additionally sensitive and appropriate testing of both the self-optimization and economy mechanism questions for human walking.

The purpose of this study was two-fold: (1) to continue examination of the self-optimization issue by including correlation analysis of PSF and RSF using a more heterogeneous human sample, and (2) to test further the resonance mechanism for walking economy by obligating individuals to walk at the RSF.

STUDY 1: RELIABILITY OF PREFERRED GAIT AND PSF/RSF CORRELATION

MATERIALS AND METHODS

Participants

Forty-seven healthy adults, 31 females and 16 males, 18 to 36 years of age, participated in this study (height: 1.71±0.10 m, mass: 73.2±15.9 kg). Participants were without previous lower extremity injury that required forced inactivity or rehabilitation within the last year and had no history of fracture or surgery within the last two years. A sizable range of height was recruited (1.51 to 1.94 m). All subjects had previous treadmill experience. The study was reviewed and approved by the institution's human subject ethics board and informed consent was obtained from all participants prior to any data gathering.

Procedures

Participants' leg lengths were measured by a single investigator as the distance from the greater trochanter of the femur to the malleolus of the fibula. Due to logistical conflicts, RSF calculations were not made for two participants. Leg length and body mass measures were combined with published estimates (Winter, 1990) to develop the whole leg hybrid pendulum model and calculate the RSF in the manner described above.

An important potential confounding factor in this line of inquiry is the introduction of a bias or a lack of consistency in the participants' understanding of the task requirements. Therefore, two instruction scripts were developed; the underlined sections were reversed in a counterbalanced fashion across participants to offset potential bias:

> *We are studying how walking economy is optimized. We know it takes effort to move: doing so economically means we get the most out of that effort. For example, if we need to walk a mile we could do it in two ways. We can walk slowly – this will be easier, but take longer. Conversely, we can walk quickly – this will increase the effort, but be done sooner. It could be that the overall cost for these two extremes, or something in-between, is the same or very different. That is what we are trying to figure out. With this in mind, we want you to walk in the way you feel is optimal.*

To obtain the preferred walking behaviors (speed, stride length, and stride frequency), subjects were asked to walk on a treadmill (Epic T60, Icon Health & Fitness, Inc., Logan, UT) according to the scripted instructions. Treadmill belt speed was calibrated manually prior to and during every session. No time limit was imposed while finding the preferred speed and participants were allowed to experience as wide a variety of speeds as they wished. Subjects would direct the investigator to increase or decrease the treadmill speed until a preferred speed was achieved for the trial. Subjects next dismounted the treadmill, the investigator randomly raised or lowered the belt speed variable amounts (participants were not informed of the adjustment), and the process was repeated. The preferred speed was identified when the subject settled on the same speed (±3%) three times in succession. No knowledge of the actual treadmill speed was available to the subject.

Upon achieving the preferred walking speed (WS) criterion for the session, participants continued walking until achieving steady state heart rate (monitored electronically; S601i, Polar Electro Oy, Finland). Heart rate (HR) was taken during this period. Preferred stride frequency (PSF) was calculated from the manually recorded period for 25 consecutive strides simultaneously. Knowing the treadmill walking speed (WS) and stride frequency (SF), stride length (SL) was calculated as per: *WS (m/s) = SL (m) x SF (strides/s).*

In this study, HR was used an indirect measure of energy expenditure, which has been shown to be valid for a broad array of applications (Keytel et al., 2005; Luke, Maki, Barkey, Cooper, & McGee, 1997; Rennie, Hennings, Mitchell, & Wareham, 2001). Walking economy (WE) was operationalized in a manner analogous to the cost of transport measure or physiologic cost index used by others (Bailey & Ratcliffe, 1995; Hagberg, Tranberg, Zugner, & Danielsson, 2010; Langman et al., 1995; Nene, 1993; Watson et al., 2011). Specifically, the task outcome product was represented by WS and combined with HR during steady state as follows: *WE (m/b) = WS (m/s) ÷ HR (b/s).*

To ensure that reliable preferred gait behaviors were obtained, each subject participated in a total of three sessions over a one-week period. Sessions were separated by at least 24 and no more than 72 hours.

Statistical Analysis

Reliability was examined in two ways. Repeated measures analysis of variance (ANOVA) was used to identify potential differences demonstrated between sessions; finding no significant differences would constitute partial evidence of reliability. Additionally, intra-class correlation analysis, which provides additional focus on the internal consistency of individual behaviors, was applied to complete the reliability assessment.

To examine the self-optimization premise, paired t-tests were applied to contrast the RSF and PSF means, as per the approach taken in many other reports. To provide a more thorough analysis of the strength of self-optimizing tendencies, the correlation coefficient was calculated with RSF as the predictor and PSF as the predicted variables. All inferential statistics used a probability level of 0.05.

RESULTS

Reliability

As presented in Table 1, the ANOVA revealed no significant differences across sessions for preferred stride frequency, stride length, and walking economy. While the walking speed and heart rate indicated some slight differences across days, they actually balanced one another, as indicated by the consistency of the economy measure. Due to this complementary balanced response and due to consistency of the basic components of stride length and frequency, we conclude the preferred gait behaviors were fundamentally consistent. Furthermore, the intra-class correlation coefficients were strong and significant for all five measures. Based on the results of both analyses, the variables

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examined for this sample demonstrated good reliability, so only the overall means are presented in Table 1.

sample missed the RSF target to a fairly large extent. This illustrates the conundrum that prompted the second study. The group analysis (t-test) indicated the PSF and RSF

Table 1
Preferred Gait Reliability: ANOVA and Intra-class Correlation Results

Variable	ANOVA $F_{2,92}$	ANOVA Probability	Cronbach's Alpha	Grand Mean	Standard Deviation
Stride Length (m)	1.01	0.368	0.893	1.36	0.18
Stride Frequency (Hz)	1.34	0.267	0.727	0.94	0.11
Walking Speed (m/s)	1.30	0.277	0.899	1.28	0.24
Heart Rate (beats/s)	1.87	0.160	0.790	1.61	0.28
Walking Economy (m/beat)	0.77	0.467	0.771	0.82	0.20

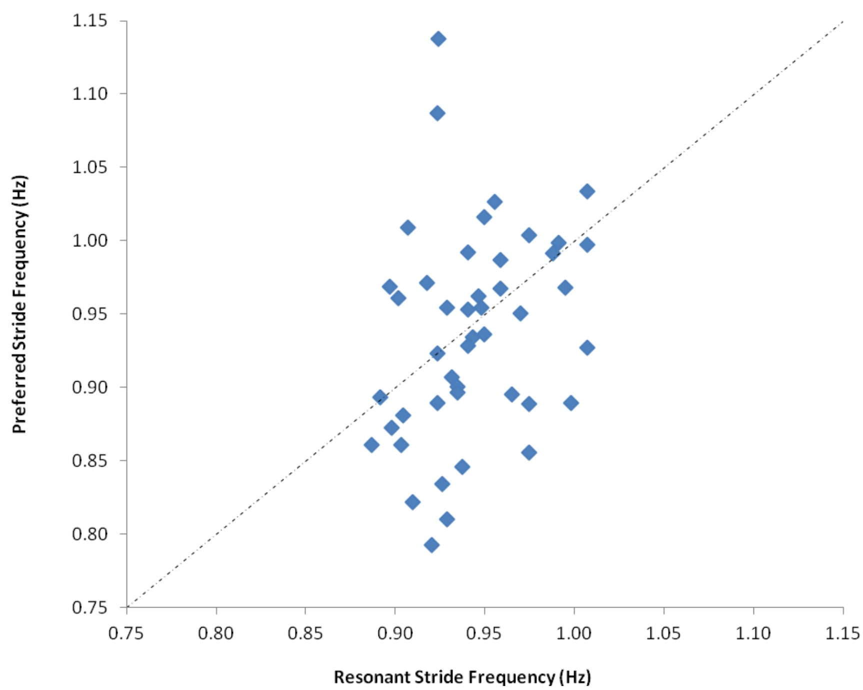

Figure 1. Scatterplot of modeled resonant (RSF) and preferred (PSF) stride frequencies. The dashed line represents a perfect correlation. While there was no significant difference between means (t_{44}=0.646, p=0.522), only 8% of the PSF variance was explained by RSF (r_{45}=0.279).

RSF / PSF Agreement

The outcomes presented in Figure 1 above clearly revealed that the mean PSF was centered on the mean RSF (only 1% apart) and also that a good portion of the were equivalent (i.e., the hypothetical average human uses the RSF), but the correlation showed that RSF was a very weak predictor of individual PSFs, which seems to be a potential challenge to a

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fundamental tenet of the self-optimization construct.

STUDY 2: ECONOMY UNDER PSF AND RSF CONDITIONS

The results from Study 1 indicated that preferred behaviors were reliable, mean PSF and RSF were functionally equivalent, and many individuals' PSF did not closely match the RSF. These findings prompted the second study, an assessment of economy when participants were obligated to use the RSF.

MATERIALS AND METHODS

Participants

A new sample of 20 individuals was recruited (6 men and 14 women, age: 21.4±1.2 years, height: 1.67±0.12m, leg length: 0.81±0.072m, mass: 70.7±14.7kg). All were healthy, college-age individuals and met the same inclusion criteria described for Study 1. The project was reviewed and approved by the institution's human subject ethics board and informed consent was obtained from all participants prior to any data gathering. Except for the specialized walking conditions modifications described below, test procedures and calculations were as detailed previously.

Procedures

HR and WS were measured and the resulting WE was calculated under three steady state treadmill walking conditions. The first condition was fully preferred, where the stride frequency, stride length, and walking speed were all unregulated (uFLS).

Two additional walking trials, performed in a counterbalanced order, were examined where participants were obligated to match the stride cadence to an audible cue from a digital metronome (DM-20 Professional 440, Seiko U.K. Ltd., Maidenhead, Berkshire) set to the RSF. This technique has been applied successfully in prior reports (Holt, Hamill, & Andres, 1991; Chen, Wing, & Pratt, 2006). In the two regulated RSF conditions participants first listened to the beat of the metronome for one minute while stationary. Once comfortable with the cadence, participants mounted the treadmill and were instructed to match heel strikes to the metronome pulse. Compliance was assessed informally by the investigator during testing. SF measures were also taken and verified post-data collection.

In one of the RSF-paced conditions the treadmill was set to the original preferred speed, consistent with other published work. It is important to note that by obligating use of the RSF and preserving the original WS, this protocol effectively dictated the SL, as well. Such regulatory constraint for the SL is not an element of the model and is logically at odds with the basic notions surrounding self-optimization. The requirement to walk under this fully regulated frequency, length and speed condition (rFLS) could produce a significantly unnatural gait pattern for subjects who did not naturally use the RSF during the initial fully unregulated walking test condition.

For this reason, a third RSF-paced condition was developed where participants were allowed to establish (using the previously described protocol) a potentially new preferred speed while using the RSF, which removed the regulation imposed on SL. This condition was viewed as more natural and thus consistent with the fundamental concept of self-optimization. The responses to this regulated frequency and unregulated length and resulting speed (rFuLS) may reveal greater detail about the role and utilization of resonance in gait economy.

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Statistical Analysis

Due to the protocol, two conditions used the RSF and two conditions used the original preferred WS. Thus, paired t-tests were applied to contrast (a) PSF and RSF and (b) the uFLS and rFuLS walking trials. Because SL, HR and WE could vary across all three of the testing conditions, repeated-measures ANOVAs were applied to examine these responses. When post hoc testing was indicated, Fisher's critical difference method was used. All inferential statistics used a probability level of 0.05.

Results

All variables analyzed demonstrated significant differences for one or more contrasts. The response patterns are illustrated in Figure 2 and the statistical results are presented in Table 2.

The most salient finding was that WE improved 14% when using the RSF and allowing for a natural stride length to be

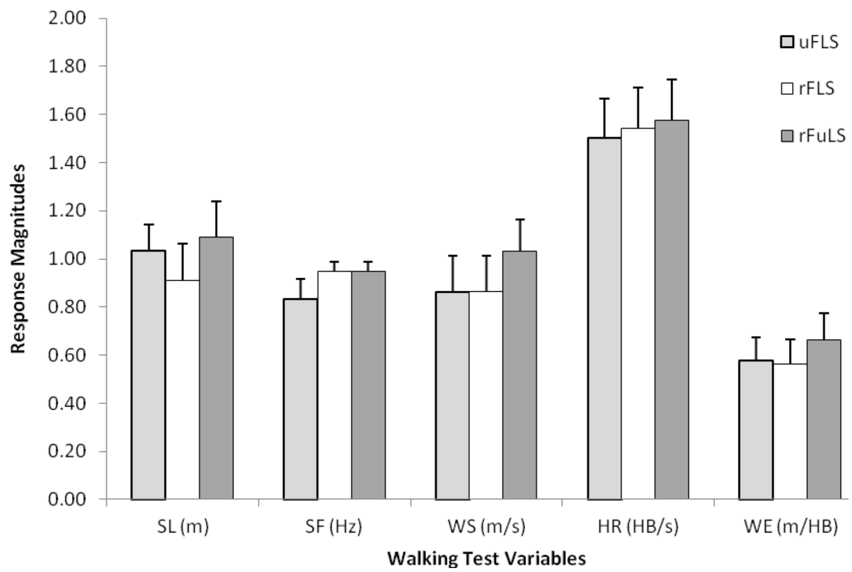

Figure 2. Illustration of each variable response across three walking condition tests. Refer to Table 2 for specific statistical results and information regarding significant contrasts. For scaling convenience HR is presented in heart beats (HB) per second. Key to walking condition abbreviations: uFLS refers to unregulated frequency, length and speed; rFLS refers to regulated frequency, length and speed; and rFuLS refers to regulated frequency and unregulated length and speed.

Table 2
Statistical Results for Walking Test Contrasts

Variable	Statistic	Ratio	Probability	Significant Contrasts
Stride Length	$F_{2,38}$	31.46	<0.001	rFLS 13% less than uFLS 5% less than rFuLS
Stride Frequency	t_{19}	8.02	<0.001	PSF 12% lower than RSF
Walking Speed	t_{19}	6.41	<0.001	(uFLS & rFLS) 19% slower than rFuLS
Heart Rate	$F_{2,38}$	12.75	<0.001	uFLS 2% less than rFLS 2% less than rFuLS
Walking Economy	$F_{2,38}$	26.62	<0.001	(uFLS & rFLS) 14% less than rFuLS

Note. Walking condition abbreviations are as follows: uFLS refers to unregulated frequency, length, and speed; rFLS refers to regulated frequency, length, and speed; and rFuLS refers to regulated frequency and unregulated length and speed.

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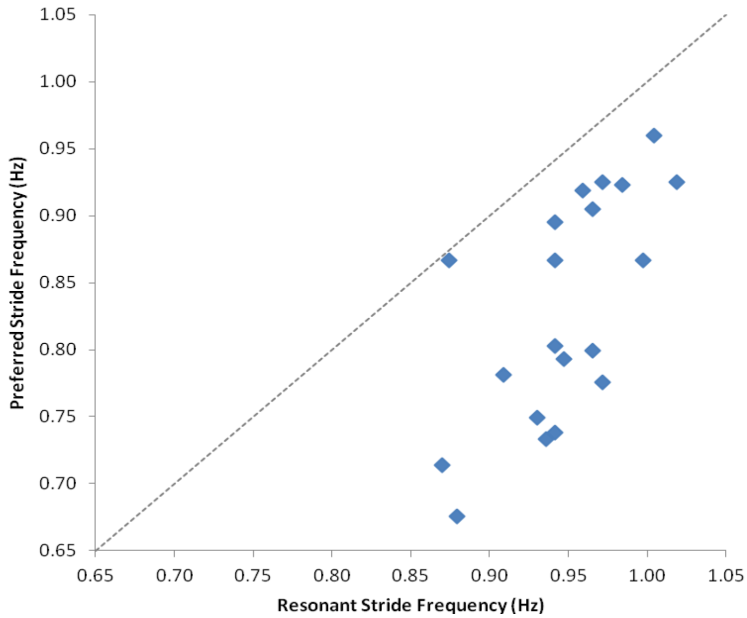

Figure 3. Relationship between resonant (RSF) and preferred (PSF) stride frequencies. While the explained variance was fairly robust (44%), the RSF-PSF mismatch and limited range of RSFs observed are apparent.

selected. For descriptive purposes and consistency with Study 1, the correlation between RSF and PSF was also determined and shown in Figure 3.

DISCUSSION

The results indicated preferred walking behaviors were generally reliable, raised slight questions about self-optimization presumptions for humans and emphasized the role of resonance in gait economy. As to the reliability of preferred gait behaviors, this was not a novel finding. However, if self-optimization is to be described as a natural or inherent characteristic of human gait, the concurrent biomechanical and physiological responses must be demonstrably reliable. Out of prudence, this aspect of preferred gait was directly assessed and confirmed for this protocol.

The more significant findings from this study relate to self-optimization and the role of resonance in gait economy. We attempted to integrate the methodologies of well-regarded research groups that examine the gait economy issue from different perspectives: (a) those with a human focus, where understanding the practical consequences for individuals tends to be emphasized, and (b) those who examine behaviors across multiple species to identify more general laws governing locomotion. To do this, we recruited a human sample with a wider range of statures and applied both types of statistical techniques typically used by the two research groups. We also developed a somewhat novel protocol we hoped would offer additional insights.

With a more heterogeneous human sample, we were able to appropriately analyze the self-optimizing tendencies of individuals via correlation. Results in

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Study 1 showed the mean RSF and PSF to be functionally equal, which is consistent with others (Holt, Hamill, & Andres, 1990; Holt, Hamill, & Andres, 1991; Holt, Jeng, & Fetters, 1991; Schot & Decker, 1998). Thus, if this human sample cluster were integrated with clusters from other walking animals, it is likely that a respectable across-species trend would be evident and the self-optimized gait characterization would be supported. However, in Study 1 more than one-third of the sample had RSF-PSF mismatches of at least 7% and the explained variance was only 8%. This level of explained variance was greater than the 4% present in Holt et al. (1990) for adult forward walking and the <1% for both forward and backward adult walking seen in Schot & Decker (1998). Though no correlation was calculated, a figure in Holt, Jeng, and Fetters (1991) clearly reveals a similar type of result. The contrasts between this and the cited studies may be attributable to the more diverse sample recruited here. In Study 2, even though explained variance was more than 40%, there actually was a significant PSF-RSF difference. Together, these observations are somewhat inconsistent with self-optimizing concepts.

It may not be surprising or concerning that many people do not walk with optimal economy. Humans, unlike other animals in their natural environments, face no great selection pressures to be economical movers, so it may be of little practical importance if many of us are inefficient. It appears that walking behavior somewhat parallels typical home mortgage decisions: in total, a 15 year mortgage is much less costly than a 30 year option, but most people choose to reduce short term expenses and incur the much greater longer term cost. However, the possibility that many actually are moving sub-optimally does represent an opportunity for performance enhancement in clinical or other practical settings. If movement economy is contextually important, it appears many have plenty of room to improve. It must be acknowledged, that even with the sample recruited for Study 1, the actual range in RSF was fairly constrained, which does hinder the utility of correlation analyses. Thus, the weak correlation may be of modest theoretical significance.

We also constructed a walking test condition where participants were allowed to self-select a stride length when using the RSF, which allowed for the possibility of a walking speed that was different from the original unregulated, preferred condition. This phenomenon did develop; a different SL was naturally paired with the RSF. We contend that the approach is more logically consistent with the basic construct of self-optimization than most previous protocols that dictate both stride length and frequency. The most economical gait did result from this more natural walking condition (approximately 14% better than the other two conditions), which actually reflects a form of self-optimizing response. Interestingly, this sample actually presented a significant difference between RSF and PSF initially. Learning and/or development are important factors in acquiring the RSF habit (Holt, Jeng, & Fetters, 1991; Holt, Saltzman, Ho, & Ulrich, 2007). Therefore, requiring use of the RSF probably represented a fairly substantive change for these subjects, yet their economy improved immediately.

The WS, SL, and HR also were greatest in this condition, however. Because the WE increased, it is clear that the WS increase was proportionally greater than the HR increase, so overall economy improved. It is possible that at higher speeds, subjects were able to take better advantage of elastic energy storage and return (Holt, Jeng, & Fetters, 1991). The stance phase of gait incurs greater amounts of muscular activity

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to support the body weight (Kuo, 2002) and a great proportion of the cost of gait has been attributed simply to weight support requirements (Kram & Taylor, 1990). Because the stance to swing ratio decreases as speed increases, it may be that less time spent in weight support contributes to a relatively decreased cost of movement, particularly if the muscle contraction velocity moves closer to its most efficient rate of approximately one-third maximum (Alexander, 1992) when using the RSF.

To reconcile the slight contradictions observed in this project, it does appear that many humans have not tuned their movements to the physical properties of their bodies, although the hypothetical average human generally presents self-optimizing gait qualities like other animals. Recognizing inherent biological variation, particularly in movement, it is unreasonable to expect every person to utilize the RSF naturally. However, when it was used, economy was enhanced immediately. The results of this study provide additional evidence for the key role of resonance for gait economy.

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