



Original Article

## Running mechanics of females with bilateral compartment syndrome

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**Abstract.** [Purpose] Primary purpose was to compare running mechanics between healthy runners and runners with chronic exertional compartment syndrome (CECS) including overstride angles, ankle dorsiflexion (DF) angles, and foot strike patterns. The secondary purpose was to analyze the association between the overstride angles and ankle DF angles. [Participants and Methods] Running images of 7 female runners with bilateral CECS patients were captured at a time of the medical examination. Their running images were compared with gender, age, and body mass index matched 31 healthy control runners. [Results] The bilateral CECS female runners have a propensity of running with significantly greater overstride and ankle DF angles than the healthy female runners. There were no foot strike differences between the two cohorts. There were a non-significant, poor relationship between overstride and ankle DF angles in the healthy female runners while a significant, strong association was found between overstride and ankle DF angles in the bilateral CECS female runners. [Conclusion] Compared to healthy female runners, bilateral CECS female runners demonstrated different running mechanics including greater overstride and ankle DF angles. The two variables were strongly associated with each other in bilateral CECS female runners, but not in healthy female runners. This may potentially contribute to the mechanism of CECS development.

**Key words:** Gait analysis, Chronic exertional compartment syndrome, Strike patterns

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### INTRODUCTION

Chronic exertional compartment syndrome (CECS) is a disorder that commonly induces pain and discomfort during exercise<sup>1)</sup>. The typical symptoms include dull aching, sharp pain, weakness, paresthesia, burning, cramping and tightness during physical activity<sup>2-5)</sup>. Symptoms typically resolve after cessation of physical activity<sup>2)</sup>, and the most prevalent body part affected by CECS is the lower leg<sup>6)</sup>. Within the lower leg, there are four major compartments: anterior, lateral, deep posterior and superficial posterior<sup>3)</sup>. Several studies reported that approximately 40–60% of CECS cases are observed in anterior compartment<sup>7-9)</sup> followed by deep posterior compartment (32–60%) and lateral compartment (12–35%)<sup>9)</sup>. One study identified a 14–33% prevalence rate of CECS in the general population and 27–33% in elite athletes<sup>2)</sup>. The etiology of the CECS is theorized that increased intracompartmental pressures decrease tissue perfusion within fascial compartment, which likely develops ischemic states<sup>10, 11)</sup>, and females are more susceptible to the CECS compared to their male counterparts<sup>12, 13)</sup>. However, the specific mechanism and the gender-specific susceptibility are still unknown<sup>2, 4, 8, 14)</sup>.

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Recent studies reported decreased signs and symptoms of CECS using gait-retraining as an intervention<sup>7, 15, 16</sup>. Using a prospective case series study design, Diebal et al. investigated the effect of gait-retraining in CECS patients<sup>15</sup>. After 6-weeks of the gait-retraining, the CECS patients showed significant decreases in compartment pressure<sup>15</sup>. Another case series investigation that employed gait-retraining as an intervention also found significant pain alleviation of CECS symptoms<sup>7</sup>. Common components of both studies were the modification of running techniques such as overstriding and foot striking patterns. Overstriding is known as a landing position of the foot relative to the knee joint<sup>17</sup>. They emphasized avoiding greater overstride and rearfoot strike patterns at initial contact in their gait-retraining. Instead, they encouraged midfoot or forefoot strike patterns<sup>7, 15</sup>. Helmhout et al. stated habitual rearfoot strike runners tend to demonstrate a longer stride length with increased ankle dorsiflexion (DF) angles at initial contact in their gaits<sup>16</sup>. The increased ankle DF leads to greater eccentric activity of anterior structures of lower shin such as tibialis anterior, which may potentially contribute to mechanism of CECS development. Therefore, avoiding rearfoot strike patterns were instructed in their prospective cohort gait-retraining study, and as the results, decreases in intracompartmental pressure, improvement in self-reported leg condition, and enhancement in running performance were identified<sup>16</sup>. Based on the evidence and rationales, we contemplated that those who have CECS possess distinctively different gait mechanics. Precisely, we hypothesized that CECS patients have a propensity to use rearfoot strike patterns, which are also associated with greater knee extension angles at strike so-called “overstride” angles and increased ankle DF at initial contact. The current study was conducted to test the hypothesis. Thus, the primary purpose of this study was to compare running mechanics between healthy runners and runners with CECS including overstride angles, ankle DF angles, and foot strike patterns. The secondary purpose was to analyze the association between the overstride angles and ankle DF angles in healthy runners and runners with CECS separately. The second purpose was postulated to gain better understanding of how each of the running mechanical components is potentially associated in the two cohorts (healthy runners and runners with CECS).

## PARTICIPANTS AND METHODS

The Institutional Review Board approval was obtained from research investigation hosting site (Boston Children’s Hospital) at beginning of this study (Protocol number: IRB-P00011000). To test our hypothesis, a retrospective case-control study design with video analysis was used. Running videos images captured between January 1, 2010 and September 15, 2014 were examined. Signatures were obtained from each participant including control healthy participants.

Medical records from patients encountered between January 1, 2010 and September 15, 2014 at the Boston Children’s Hospital were thoroughly reviewed. Following inclusion criteria was used: 1) Diagnosis of bilateral CECS was made, 2) The CECS diagnosis was performed by a combination of medical examination and compartment pressure test, 3) CECS patients are engaging with running activities at a time of clinical visits, 4) “Patients” running images were captured at a time of the medical examination, and 5) Gender is female. The bilateral CECS patients were selected in order to strengthen the internal validity between the CECS pathology and running mechanics. Female gender was selected to maintain homogeneous population group instead of a combination of both males and females. Exclusion criteria were: 1) Unilateral or no CECS diagnosis, 2) Absence of either medical or compartment pressure test, 3) Non-engagement in running activities at a time of clinic visit, 4) Missing running images, and 5) Male gender. In addition to the five exclusion criteria, a history of previous surgeries in lower extremity including fasciotomy and presence of other musculoskeletal conditions were excluded. Based on the injured runners’ gender, age, and body mass index (BMI), matched healthy runners were selected, and their running images were compared for the purpose of this study. The video images were analyzed using ImageJ software (US National Institutes of Health, Bethesda, 176 MD, USA).

As a part of medical care, patients who sustained a running-related injury have been evaluated through gait analysis at The Micheli Center for Sports Injury Prevention. Also, runners without any pathology had access to The Micheli Center for Sports Injury Prevention for their gait analyses. Following steps were used for a gait analysis. Participants performed a warm-up prior to treadmill running. The warm-up included general stretching and slow-pace running on the treadmill, which took up to 5 minutes. The general stretching was performed by self-selected formats, and quadriceps, hamstrings, lateral thigh musculature, and calves were routinely stretched. Following the warm-up, each participant selected their treadmill speeds based on their comfort level. Video recordings began after participants reported adequate warm-up status and felt comfortable running on treadmill, which was usually middle of the running test. Treadmill speeds varied, but all participants ran a range of speeds of 4–5 mph. All recordings were performed with a treadmill slope grade of 0 (horizontal to the ground).

Running images were recorded by two different high-speed cameras on a level treadmill. The Casio Exlim 1 at 300 frames per second (Casio, llc, Tokyo, Japan) was used for this study. Total video lengths varied from 10 seconds to 30 seconds per plane. Images were recorded typically in the order from posterior view for coronal/frontal plane and then side view for sagittal plane. Three coronal/frontal plane images from the posterior views were taken: full body, hip and below, as well as knee and below. Two sagittal plane images from side views were taken: full body, as well as hip and below.

Following definitions were used to attain our study purposes:

- Overstride angle: From side view on sagittal plane at the moment of initial contact, angle generated between a vertical line and either a line drawn from the lateral malleolus to the fibular head or a line from the center of the knee to the malleolus. Angle measurement anterior to the fibular head or knee was considered positive angles. Angle measurements posterior to the

fibular head or knee were considered negative angles (Fig. 1).

- Ankle DF angle: From side view on sagittal plane at the moment of initial contact, angle generated from a line between the fifth metatarsal head or first metatarsophalangeal joint to the heel and a line from the fibular head through malleolus (Fig. 2).

- Foot Strike pattern: Determined at the moment of initial contact of the foot with the treadmill surface at the moment of impact using side views at sagittal plane; defined as rearfoot strike if the heel hit first, forefoot strike if the ball of the foot hit first, or midfoot strike if the fore-foot and rear-foot struck the ground simultaneously<sup>18</sup>).

Review of the running video images was performed under a rigorous blinding protocol among all study members who were involved in the data analysis. All information that could potentially indicate a runners' study group (case vs. control) was concealed during the data analysis process. In order to minimize bias, video images were compiled and then randomized using an automatic randomization function in Microsoft Excel by one study personnel (personnel 1). A mechanical engineering student (personnel 2) who did not participate in the data collection, organization and randomization components reviewed all images through the imageJ. The study personnel (personnel 3) who performed statistical analysis was also blinded from the assignment of participants' study grouping, video selection, the video analysis processes. The blinding was maintained until the entire data analysis process was completed.

The physical characteristics such as age, height, weight and BMI were compared between runners with bilateral CECS and healthy runners. Mean overstride and ankle DF angle values of right and left limb of the two cohorts were compared by Student's t-test when normally distributed. When normal distribution was not observed, Mann-Whitney U test was employed. Status of the normality was tested by Shapiro-Wilk test. In addition to comparison of mean and standard deviation, 95% confidence interval and effect size measures were incorporated. The effect size was assessed by Cohen's d, and following criteria were applied:  $<0.20$ =small,  $0.21-0.50$ =small to medium,  $0.51-0.80$ =medium to large, and  $>0.8$ =large<sup>19</sup>). Foot strike types (rearfoot, midfoot, and forefoot) were compared in right and left foot separately between the two cohorts using a  $\chi^2$  analysis. To identify association between the overstride and ankle DF angles, Pearson correlation coefficient analysis was performed separately in the each cohort. The strength of the association was evaluated by correlation coefficient (r) value and was defined as  $<0.3$ =poor,  $0.3-0.5$ =fair/moderate,  $0.5-0.7$ =good, and  $>0.7$ =strong<sup>20</sup>). The a priori significance (alpha level) was set at  $p=0.05$ , and the IBM SPSS statistical software (Version 23, SPSS Inc, Chicago, IL, USA) was employed for all analyses.

## RESULTS

A total of 38 patients were included: 7 runners with bilateral CECS and 31 healthy runners as a control. Since all 7 runners with CECS were females, a cohort of healthy control runners consisted of all females. Physical characteristics of the two cohorts were displayed at Table 1. There were no differences in physical characteristics including age, height, weight, and BMI between the two groups (Table 1). The Mann-Whitney U test identified that the bilateral CECS female runners had a propensity of running with greater overstride ( $p=0.036$ , Table 1) and ankle DF angles ( $p=0.021$ , Table 1) than the healthy control female runners.



**Fig. 1.** Image of overstride angle measurements at initial contact.

Overstride angles was calculated between a vertical line drawn from the lateral malleolus to the fibular head. Angle measurement anterior to the fibular head or knee was considered positive angles. Angle measurements posterior to the fibular head or knee were considered negative angles.



**Fig. 2.** Image of ankle DF angles measurements at initial contact.

Ankle DF angle was calculated from a line drawn from the fifth metatarsal head to the heel and a line from the fibular head through malleolus.

Large effect was found in both overstride (Cohen's  $d=1.08$ ) and ankle DF angles (Cohen's  $d=1.14$ ). There were no foot strike type differences in both right ( $p=0.604$ , Table 2) and left ( $p=0.523$ , Table 2) sides between the two cohorts.

There was a non-significant, poor relationship between the overstride and ankle DF angles in the healthy control female runners ( $r=0.213$ ,  $p=0.267$ ) while a statistically significant, strong association was found between the overstride and ankle DF angles in the bilateral CECS female runners ( $r=0.813$ ,  $p=0.026$ ).

## DISCUSSION

The purpose of this study was to compare running mechanics between runners with CECS and healthy runners, and we hypothesized that CECS runners demonstrate different mechanics compared to healthy runners, precisely more rearfoot strike patters, greater overstride, and ankle DF angles at initial contact. Although there were no significant differences in propensity of the foot strike patterns (Table 2), overstride and ankle DF angles were significantly different between the two groups (Table 1). Additionally, an interesting finding was the strong association between the overstride and ankle DF angles in the CECS cohort while the strength of association was poor in the healthy control runners. Several studies implemented a gait-retraining as a non-invasive intervention for CECS and reported positive outcomes including compartmental pressure reduction, patient outcome scale improvement, and running performance recovery<sup>15, 16, 21</sup>). Although the positive clinical,

**Table 1.** Comparison of physical characteristics and running mechanics between runners with bilateral CECS and healthy control runners

	Runners with bilateral CECS (N=7)	Healthy control runners (N=31)
Physical characteristics		
Age (years)	17.9 ± 2.1	20.4 ± 5.4
Height (cm)	165.3 ± 8.2	163.7 ± 6.9
Weight (kg)	60.1 ± 10.2	55.2 ± 5.9
BMI (kg/m <sup>2</sup> )	21.9 ± 2.3	20.6 ± 1.9
Running mechanics		
Overstride angle (degrees)		
Right	11.2 ± 3.7 (7.8, 14.6)	8.4 ± 2.5 (7.4, 9.4)
Left	10.7 ± 3.7 (7.2, 13.9)	7.5 ± 2.6 (6.5, 8.5)
Mean values*	10.9 ± 3.4 (7.8, 13.4)	7.9 ± 2.0 (7.1, 8.7)
Ankle DF angle (degrees)		
Right	17.7 ± 4.0 (14.0, 21.3)	13.3 ± 4.6 (11.4, 15.1)
Left	20.3 ± 3.9 (16.7, 23.8)	16.5 ± 5.1 (14.5, 18.5)
Mean values*	19.0 ± 3.0 (16.2, 21.7)	14.9 ± 4.1 (13.3, 16.5)

Values are mean ± standard deviation. 95% CI values are expressed within brackets. \*Mean overstride angles were statistically different between runners with bilateral CECS and healthy control runners ( $p=0.036$ ).

\*Mean ankle DF angles were statistically different between runners with bilateral CECS and healthy control runners ( $p=0.021$ ).

**Table 2.** Comparison of foot strike patterns between runners with bilateral CECS and healthy control runners

	Runners with bilateral CECS (N=7)	Healthy control runners (N=31)	Total
R foot strike patterns			
Rearfoot strike	7 (100%)	27 (87.1%)	34
Midfoot strike	0 (0.0%)	1 (3.2%)	1
Forefoot strike	0 (0.0%)	3 (9.7%)	3
L foot strike patterns			
Rearfoot strike	7 (100%)	26 (83.9%)	33
Midfoot strike	0 (0.0%)	3 (9.7%)	3
Forefoot strike	0 (0.0%)	2 (6.5%)	2

patient-oriented, and performance outcomes of gait-retraining were reported, the mechanism was not fully understood. Although the present study was preliminary, findings may potentially help understanding the gap in the mechanism and also may further assist facilitating more effective gait-retraining program development for CEDS patients.

Our results indicated that runners with CECS showed greater ankle DF angles at initial contact than the healthy control runners. The etiology of the CECS is theorized, however, the specific mechanism is still under investigations<sup>2, 4, 8, 14</sup>). One of the most accepted theories of CECS development is that inflated compartmental pressures reduce tissue perfusion within fascial compartment, which results in ischemic states<sup>10</sup>). According to a study performed by Tsintzas et al., significantly increased intracompartmental pressure of both anterior and deep posterior compartments was observed when the ankle is dorsiflexed<sup>22</sup>). In our study cohort, all 7 runners had a positive CECS diagnosis at the anterior compartment bilaterally, and 2 of the 7 runners also had additional CECS diagnosis in deep posterior compartments. The clinical pathology of the enrolled CECS patients in the current project was aligned well with the evidence generated by Tsintzas et al.<sup>22</sup>). This increased ankle DF angles may potentially lead to constant activation state of tibialis anterior muscles, and repetitive stress during running with increased ankle DF angles at initial contact might have contributed the development of CECS in our cohort.

Furthermore, the greater ankle DF angles recorded in the CECS runners were significantly and strongly associated with the increased overstride angles. This finding indicates that the greater ankle DF angles one has, the greater overstride angles in one's running mechanics are. This "overstride" angles were often discussed among the runners' community, but scientific evidence was sparse<sup>23-25</sup>). However, a recent study performed by Lieberman et al. reported that greater overstride angles are associated with increased rate and magnitude of the vertical ground reaction impact peak<sup>17</sup>). Another study conducted by Kuhman et al. reported that the greater loading rate of ground reaction impact peak and increased ankle DF moment was found in habitual rearfoot strike runners<sup>26</sup>). Moreover, examining a group of collegiate cross country runners, Daoud et al. found that musculoskeletal injuries were more common in those who have a rearfoot strike than either midfoot or forefoot strike patterns<sup>27</sup>). Finally, a recent meta-analysis study concluded that a high loading of vertical ground reaction force in running is suggestive to running related musculoskeletal injury, especially stress fracture<sup>28</sup>). To synthesize evidence from the past studies to our finding, it is assumed that the cohort of runners with bilateral CECS ran with greater loading of vertical ground reaction force during their running, which was facilitated by the greater overstride along with the greater ankle DF angles. Even though  $\chi^2$  tests did not show significantly different strike patterns between CECS runners and gender, age, and BMI matched healthy control runners, all CECS runners demonstrated a propensity of rearfoot strike at initial contact bilaterally (Table 2). Since one of the past studies indicated more frequent musculoskeletal injuries among rearfoot strikers<sup>27</sup>, and greater loading rate of ground reaction impact peak with increased ankle DF moment<sup>26</sup>) and overstride angles<sup>17</sup>), it is reasonable to consider that altering the overstride and ankle DF angles likely help reducing the high rates of vertical ground reaction impact peak loading during gait-cycle. Practical training application of reduction in the overstride angles includes bringing the ankle in a more vertical direction relative to the knee at footstrike during running, which likely facilitates altering the foot strike propensity from rearfoot to either midfoot or forefoot pattern.

In past studies<sup>7, 15, 16</sup>), core of the gait retraining interventions to CECS patients was to alter the foot strike patterns from rearfoot to either midfoot or forefoot pattern. In the current study, there were no foot strike propensity differences between the bilateral CECS patients and healthy control runners, which may be due to a small sample size. However, healthy control runners demonstrated more variations in the footstrike patterns (Table 2). Based on this observation and past studies<sup>7, 15, 16</sup>), the type of the foot strike patterns potentially have clinical relevance on CECS conditions. In addition to the specific foot strike patterns, increased ankle DF angles at initial contact might have triggered a persistently high level of anterior muscle tensions in CECS patients, which might have hindered a normal tissue perfusion and contributed elevated intracompartmental pressure. The results of this study indicated a strong association between ankle DF and overstride angles only in CECS patients, but not in healthy control runners; thus, reducing the overstride angles at initial contact may optimize ankle DF angles. Emphasizing reduction in overstride angles likely facilitate shorter step distance and further assist higher step rates during gait-cycle. A study performed by Luedke et al. reported that lower step rates are associated with greater likelihood of sustaining shin injury<sup>29</sup>). Hence, greater step rates may help decreasing stress at shin segment. Additionally, Diebal et al. documented alleviations of symptoms once higher step rates of running patterns were attained by CECS patients<sup>15</sup>). In short, because of the strong association between overstride angles and ankle DF angles found only in CECS runners, changing the overstride angles may alter foot strike patterns and potentially promote higher step rates. Those components may be beneficial for gait re-training.

Clinical implication of the study outcomes needs to be noted. CECS diagnosis can be delayed due to the multitude of symptoms, and potentially differential diagnoses. To receive a clinical diagnosis of CECS, patients must undergo pre and post exercise intra-compartmental pressure testing, an invasive measure, to test the pressure difference and identify which compartment(s) are being affected<sup>10</sup>). Currently, common non-invasive treatments of CECS include cessation of physical activity, anti-inflammatories, ice, stretching, massages and orthotics<sup>2, 7, 15</sup>). Invasive treatment for CECS is fasciotomy, which involves cutting the fascia surrounding the effected compartment. However, up to 35% of CECS recurrence rate was reported following a fasciotomy<sup>8</sup>). It has also been reported that females and those with deep posterior compartment syndrome respond less favorable to fasciotomy and are more likely to have a recurrence of symptoms<sup>2, 13, 30</sup>). The etiology of CECS recurrence rate is largely unknown; however, faulty running mechanics may potentially modulate physiologically harmful effects on the lower shin, which may be resulted in CECS. Therefore, if the specific gait patterns and the fairly high recurrence rate of



CECS are established, modification of the gait mechanics may potentially reduce recurrence of the CECS. Furthermore, the modification of the gait mechanics is a non-invasive treatment. Therefore, it may be more easily implemented and executed by healthcare practitioners who are engaging with running training and cares, which may also potentially decrease medical costs associated with CECS.

Inherent limitations of this study included a small number (N=7) of CECS patients. However, they were bilateral CECS patients. We used mean of both right and left limbs to compare the overstride and ankle DF angles so that the data consisted of 14 limbs of CECS patients. In addition, because this study was conducted using a retrospective case control study design, training dosage such as training frequency, training length, and season duration were not included in this analysis. However, running mileages of the runners in this study were estimated a range of 12–18 miles (19–29 kilometer) per week. Finally, the current study cohort consisted of all females. Although the past evidence suggested that CECS is more common in females than males<sup>31, 32</sup>, future studies are warranted to include a male population.

In summary, the current study compared gait mechanics including overstride angles, ankle DF angles, and foot strike patterns between bilateral CECS female runners and gender, age, BMI matched healthy female runners. The bilateral CECS female runners showed greater overstride and ankle DF angles relative to healthy control female runners. Also, a significantly strong association was found between the overstride and ankle DF angles in bilateral CECS female runners, but not in the healthy control female runners. These findings may help developing a non-invasive treatment for CECS patients such as gait-retraining. Since this study only had female runners, future studies need to incorporate male population in order to provide more generalizable evidence.

Findings of this study deliver clinically important knowledge. In this study, female runners with bilateral CECS demonstrated greater overstride ( $p=0.036$ ) and ankle DF angles ( $p=0.021$ ) in their running than age, gender, and BMI matched healthy control. They are also strongly associated with each other only in female runners with bilateral CECS ( $r=0.813$ ,  $p=0.026$ ), but not in healthy control runners ( $r=0.213$ ,  $p=0.267$ ). The evidence supports a possibility of optimizing CECS condition by a non-invasive intervention such as a gait modification, education, and training. Several studies implemented a gait-retraining to CECS patients, and the result indicated favorable sign/symptom changes, decreased compartmental pressure, and better patients-oriented outcome survey scores and return to running performance. Current standard care for the CECS is fasciotomy, which shows a fairly high recurrence rate. Also, surgery requires more financial burden to each patient. Therefore, more studies are necessary to substantiate current findings and to pursue a development of non-invasive treatments for CECS patients.

### *Conflict of interest*

None.

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