Published in final edited form as:

Gait Posture. 2020 January ; 75: 142–148. doi:10.1016/j.gaitpost.2019.10.025.

Chronic obstructive pulmonary disease patients increase medio-lateral stability and limit changes in antero-posterior stability to curb energy expenditure

Farahnaz Fallahtafi^a, Carolin Curtze^a, Kaeli Samson^b, Jennifer M. Yentes^a

^aDepartment of Biomechanics, University of Nebraska at Omaha, 6160 University Drive South, Omaha, NE 68182-0860

^bDepartment of Biostatistics, University of Nebraska Medical Center, 984375 Nebraska Medical Center, Omaha, NE 68198-4375

Abstract

Background: A relationship exists between step width and energy expenditure, yet the contribution of dynamic stability to energy expenditure is not completely understood. Chronic obstructive pulmonary disease (COPD) patients' energy expenditure is increased due to airway obstruction. Further, they have a higher prevalence of falls and balance deficits compared to controls.

Research question: Is dynamic stability different between COPD patients and controls; and is the association between dynamic stability and energy expenditure different between groups?

Methods: Seventeen COPD patients (64.3 ± 7.6 years) and 23 controls (59.9 ± 6.6 years) walked on a treadmill at three speeds: self-selected walking speed (SSWS), -20% SSWS, and $+20\%$ SSWS. Mean and variability (standard deviation) of the anterior-posterior (AP) and medio-lateral (ML) margins of stability (MOS) were compared between groups and speed conditions, while controlling for covariates. Additionally, their association to metabolic power was examined.

Results: The association between stability and power did not significantly differ between groups. However, increased metabolic power was associated with decreased MOS AP mean ($p < 0.0001$), independent of speed. Increased MOS AP variability ($p = 0.01$) and increased SSWS ($p < 0.05$) were associated with increased metabolic power.

Corresponding Author: Dr. Jennifer M. Yentes, University of Nebraska at Omaha, 6160 University Drive, Omaha, NE 68182-0860, Phone: 402-554-3251, Fax: 402-554-5938, jyentes@gmail.com.

CRediT roles:

Farahnaz Fallahtafi: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Writing - original draft; Writing - review & editing. **Carolin Curtze:** Methodology; Writing - review & editing. **Kaeli Samson:** Formal analysis; Writing - review & editing. **Jennifer Yentes:** Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing - review & editing.

Conflicts of Interest

The authors have no conflicts of interest to disclose.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

The MOS ML mean for COPD patients was greater than that of healthy patients ($p=0.02$). MOS AP mean decreased as speed increased and differed by group ($p=0.048$). For COPD patients, a plateau was observed at SSWS and did not decrease further at +20%SSWS compared to controls. MOS AP variability ($p<0.0001$), MOS ML mean ($p<0.0001$), and MOS ML variability ($p=0.003$) decreased as speed increased and did not differ by group.

Significance: Patients with COPD operate at the upper limit of their metabolic reserve due to an increased cost of breathing. To compensate for their lack of stability, they walked with larger margins of stability in the ML direction, instead of changing the stability margins in the AP direction, due to its association with energy expenditure.

Keywords

pulmonary disease; metabolic power; extrapolated center of mass; dynamic stability

INTRODUCTION

Chronic obstructive pulmonary disease (COPD) is the third leading cause of death in the United States [1], affecting not only the lungs but also the muscular system [2] leading to deficits in functional performance [3]. Patients with COPD have balance impairments that increase with disease exacerbation [4]. Balance impairments can lead to falls, fear of falling, and even mortality, as well as higher cost of healthcare [5]. Compared to the rate in which healthy, non-COPD persons fall each year, patients with COPD have a higher susceptibility to fall [6]. Patients with COPD have stability deficits while walking as documented through increased spatiotemporal variability [7] and trunk acceleration variability in medio-lateral direction [8]. One important aspect of gait variability is its relationship to fall risk [9] and stability [10].

In recent years several methods have been proposed to assess changes in stability during walking [10]. Gait stability has been quantified based on the concept of extrapolated center of mass as the ability to control the velocity-adjusted position of the body's center of mass (COM) over its moving base of support (BOS) [11, 12]. Originally, MOS was introduced to describe control of balance during walking in the medio-lateral (ML) direction [11, 12]. In the ML direction, stable gait is achieved by placing the center of pressure at a certain distance laterally to the right or left of the (extrapolated) COM, thereby redirecting its moment [12]. In this case, a positive MOS indicates that the extrapolated COM is within the lateral boundaries of the BOS. Studies have begun to calculate MOS in the anterior-posterior (AP) direction [13, 14]. Walking at a steady speed in the AP direction is inherently unstable as the center of pressure needs to be placed at a certain distance behind the extrapolated COM [12]. Therefore, the extrapolated COM exceeds the boundaries of the BOS indicating instability, which is needed for forward progression during walking [15]. In this case, a negative MOS indicates the extrapolated COM is outside of the BOS. MOS mean is the average distance between the extrapolated COM and the limit of the BOS. MOS variability reveals information about step-to-step variations in the control of foot placement. Increased MOS variability may be reflective of an increased frequency of adjustments and corrective responses of foot placements. Decreased dynamic stability can be described as decreased mean and/or increased variability of MOS.

There is a possible tradeoff between gait economy and stability. In persons with an incomplete spinal cord injury, decreases in balance control were associated with increased metabolic energy required for lateral stabilization [16]. Further, in healthy adults, decreased variability in foot placement was accompanied by mild but significant decreases in metabolic cost. Humans prefer a step width that minimizes metabolic cost [17]. Patients with COPD choose their walking speed to keep gait variability and energy expenditure at a suitable level [7]. Walking at speeds different from self-selected speed is more demanding metabolically [18]. Moreover, gait variability which is related to the stability of walking [9], is altered during faster and slower speeds compared to preferred speed of walking [19]. Maintaining dynamic stability during speeds different from a self-selected speed may be costlier in energy expenditure. In addition, preferred stride time and length combination for a particular speed may lead to the minimal metabolic cost [20]. To date, few studies have explored gait mechanics and reported gait deficits in patients with COPD [7, 21]; however, to our knowledge there is no study comparing the association between dynamic stability and energy expenditure in patients with COPD.

To investigate dynamic stability in patients with COPD, we measured the MOS means and variabilities in three different walking speeds and compared the results while considering covariates. We hypothesized that patients with COPD would have decreased dynamic stability in AP and ML directions in comparison with healthy controls. Considering the balance impairments and increased cost of walking in patients with COPD [22], we also aimed to study the association of MOS to energy expenditure while walking. It was hypothesized that MOS and speed would be significant contributing factors to energy expenditure. According to deficits in balance control in patients with COPD, which are associated with reduced physical activity and muscle weakness [23], we expected to observe a differential contribution of MOS to energy expenditure between the two groups.

METHODS

Participants

This investigation was a secondary analysis of a previous study [22]. Seventeen patients with COPD and 23 healthy controls participated (Table 1). Spirometry testing was performed on all subjects to define the presence of COPD [24]. Participants were excluded if they had an injury or surgery affecting their mobility, and/or a diagnosis of neurological, musculoskeletal, cardiovascular disease, or other pulmonary disorders. The Institutional Review Board reviewed and approved all procedures.

Data collection

Participants were asked to wear a form-fitting suit and retro-reflective markers were placed on defined anatomical locations [7]. Participants were outfitted with a portable metabolic measurement unit to measure breath-by-breath pulmonary gas exchange (K4b²; Cosmed USA Inc., Concord, CA). Resting heart rate and metabolic rate were measured in a relaxed, quiet standing position for five minutes. All participants were asked to walk on a treadmill (AMTI, Watertown, MA) at the speed they were comfortable walking casually to determine their self-selected walking speed (SSWS) [7]. After a minimum of two minutes rest, and

once resting heart rate returned to baseline, they were asked to walk at their SSWS for six-minutes. Two remaining fast and slow speed conditions ($\pm 20\%$ of SSWS) were performed in randomized order. Marker trajectories (120 Hz; Motion Analysis Corp., Santa Rosa, CA) and breath-by-breath metabolic data were analyzed for the last four minutes of each trial.

Data Analysis

Gait stability was quantified based on the ability to control the velocity-adjusted position of the body's COM over its moving BOS. To calculate the velocity-adjusted position of the body's COM, we calculated extrapolated COM (XcoM) defined as follows:

$$X_{coM} = COM + \frac{v_{COM} + v_{BOS}}{\omega_0}$$

where the COM position was estimated as the average position of the four pelvis markers (right and left anterior and posterior superior iliac spines) [14], v_{COM} represented the velocity of the COM adjusted for the treadmill velocity v_{BOS} . The eigen frequency of the pendulum was defined as

$$\omega_0 = \sqrt{g/l}$$

where g represented the acceleration of gravity and l was the effective pendulum length defined as the distance from the COM to the lateral right and left ankle markers at heel strike. MOS was calculated as:

$$MOS = BOS - X_{coM}$$

where BOS was defined using heel markers in AP direction (the approximate location of center of pressure at the heel strike) and lateral metatarsal phalangeal markers in ML direction. MOS was calculated in both the AP and ML directions at heel strike for each right and left step. Heel strikes were defined as the peak position of the heel marker in the AP direction. MOS variability was calculated as the standard deviation of each speed trial.

Cost of transport (energy expenditure per unit of distance) was calculated as previously reported [22] and converted to metabolic power (energy expenditure per unit of time) [25]. Lastly, spatiotemporal gait variables step length, step time, and step width were calculated as previously reported [7]. All calculations were performed using custom MATLAB programs (2016b; The MathWorks, Natick, MA).

Statistics

Scatter plots of the outcome variables versus speed of walking were created (Supplemental Figure S1). Data were summarized using counts or means and standard deviations separately for patients with COPD and healthy controls. Differences in demographics and characteristics between groups were assessed using t-tests. Repeated measure ANOVA was used to compare the metabolic power between the two groups and three speed conditions. To

determine which covariates were to be included in the models, Pearson correlation coefficients were calculated between outcome variables (all measures of stability and metabolic power) and spatiotemporal variables (SSWS, step length, step time, and step width). Spatiotemporal variables with a significant correlation were included as a covariate. To assess differences in stability, linear mixed models were run, one for each MOS variable (AP or ML, mean or variability) as the outcome, and included group, speed condition, relevant spatiotemporal covariates, and any significant interactions involving the group variable. If an interaction was significant, a subgroup analysis was performed, where separate models were run for each group. To assess the association between metabolic power and stability, four separate linear mixed models were run, one for each MOS predictor, with metabolic power as the outcome, which also included group, speed condition, SSWS, and the interaction between group and the MOS predictor, if significant. SSWS was selected as a potential covariate instead of actual walking speed of the three conditions to avoid collinearity with the speed condition variable. The Tukey-Kramer adjustment method was used for multiple post-hoc comparisons. All analyses were performed using SAS (version 9.4, SAS Institute Inc., Cary, NC) or SPSS (version 23, IBM Corp., Armonk, New York). Alpha was set at 0.05.

RESULTS

There was a significant group by speed interaction for metabolic power, indicating that metabolic power was lower in patients with COPD compared to healthy controls, more so in faster speed conditions ($F(1.47, 56.1) = 3.919$, $p = 0.037$; Figure 1). SSWS was significantly correlated with both MOS AP mean (range $r = -0.55$ to -0.79) and standard deviation (range $r = -0.48$ to -0.49). Thus, SSWS was entered into the AP models as a covariate. Step width during all three speed conditions was significantly correlated to MOS ML mean (range $r = 0.46$ to 0.52) and standard deviation (range $r = 0.28$ to $r = 0.34$); thus, was entered into the ML models as a covariate.

MOS AP mean

In the MOS AP mean model, after controlling for SSWS, there was a significant interaction between group and speed condition ($p = 0.048$). For healthy controls, there were significant differences in MOS AP mean between all speed conditions (p 's < 0.001), where the -20% SSWS condition had the largest MOS, and the $+20\%$ SSWS condition had the smallest MOS. However, for the patients with COPD, the -20% SSWS condition had a significantly larger margin of stability than the SSWS ($p < 0.0001$) and $+20\%$ SSWS conditions ($p < 0.0001$), but the SSWS and $+20\%$ SSWS conditions did not significantly differ ($p = 0.69$).

MOS AP variability

No significant difference in the MOS AP variability model-adjusted estimates between patients with COPD and healthy controls was found ($p = 0.26$). However, a significant difference in MOS AP variability between speed conditions was found after adjusting for group and SSWS ($p < 0.0001$; Figure 2, Table 2). Specifically, -20% SSWS had significantly more AP MOS variability compared to $+20\%$ SSWS and SSWS ($p < 0.0001$ and $p = 0.001$,

respectively). No significant interactions involving group were found for MOS AP variability.

MOS ML mean

MOS ML mean was significantly different between groups. After adjusting for step width, MOS ML mean for patients with COPD was larger than that of healthy controls ($p=0.02$). Additionally, model adjusted MOS ML mean was different between speed conditions ($p<0.0001$). After adjusting for group and step width, +20%SSWS and SSWS had a smaller MOS ML mean compared to -20%SSWS (both $p's<0.0001$). No significant interactions involving group were found.

MOS ML variability

After adjusting for step width, and although not significant, MOS ML variability in patients with COPD was greater than healthy controls ($p=0.07$). On the other hand, MOS ML variability significantly differed by speed condition after adjusting for group and step width ($p=0.003$). Specifically, SSWS had less MOS ML variability than -20%SSWS ($p=0.002$). No significant interactions involving group were found.

Metabolism

None of the metabolic outcome models had significant interactions between MOS and COPD status, indicating that the association between stability and power did not significantly differ by COPD status. Therefore, only main effect of group or speed condition were presented (Table 3).

Increased MOS AP mean was associated with decreased metabolic power ($p<0.0001$), and conversely, increased MOS AP variability was associated with increased metabolic power ($p=0.01$) (models adjusted for COPD status, SSWS, and speed condition). MOS ML mean and variability were not associated with metabolic power. Furthermore, model-adjusted SSWS was significantly associated with metabolic power in all models except for MOS AP mean (AP variability $p=0.002$, ML mean $p=0.01$, ML variability $p=0.01$).

DISCUSSION

This study investigated if the association between stability and energy expenditure differed by COPD status. The contribution of MOS to energy expenditure was not different between groups. It was found, for both groups, MOS AP mean did contribute to energy expenditure. These results coincided with a group by speed condition interaction for MOS AP mean. Controls significantly decreased margins of stability as speed increased; however, patients with COPD did not decrease margins from SSWS to the fastest speed. In the ML direction, patients with COPD had an increased mean MOS during all speed conditions compared to controls. Whilst, compared to controls, patients with COPD had lower metabolic power across all speeds. Collectively, these results indicate that patients with COPD may alter ML stability and limit alterations in AP stability. It is plausible that this is due to the association of AP stability with energy expenditure. These patients operate at the upper limit of their metabolic reserve due to an increased cost of breathing. Poor lung function, muscle

dysfunction, and chronic systematic inflammation [2] affect both metabolic cost (due to an increase in the work of breathing and the use of systemic steroids [26]), and stability control (due to the gait deviations and muscle weaknesses [2, 23]) during walking. Their selected AP stability margins may reach toward the upper metabolic capacity limit while walking at preferred speed. Thus, to avoid increasing energy expenditure further, patients with COPD experienced plateaued MOS in the AP direction as speed increased. An alternative explanation could be this association between MOS AP mean and metabolic power is mediated through speed. However, this does not appear to be the case. Faster SSWS was associated with greater energy expenditure in all models except for MOS AP mean, indicating that MOS AP mean was associated with energy expenditure independent of speed.

Despite altered ML margins in patients with COPD, we did not find any overall association between energy expenditure and ML measures of stability. Manipulation of gait patterns leads to alterations in energy expenditure [17], which may affect its association with dynamic stability. For example, step width is actively determined in accordance with the foot placement with respect to the COM movements during walking [27]. Further, humans use active control to maintain ML stability during walking, which also increases energy expenditure [28]. In our study all participants walked with their preferred step width and walking pattern. Allowing the freedom to explore preferred step width may lead to the minimum energy expenditure during walking.

Both groups did adjust foot placement relative to the projection of the extrapolated COM to control lateral stability. MOS variability indicates how well people control their COM over the BOS in different conditions [14]. Increased MOS variability may reflect increased adjustment frequency and corrective responses of foot placements. Although, increased MOS ML variability in patients with COPD did not reach significance, it could be an indicator of an inability to control stability and/or foot placement in ML direction as a result of impaired muscle function in patients with COPD [2].

Altering the speed of walking coincided with significant changes in MOS. In both groups of participants MOS ML mean and MOS AP and ML variability decreased as speed increased. Increased momentum during the fastest speed could be a potential factor for increasing the instant velocity of COM. Body momentum must be controlled to maintain stability during walking, and decreasing gait velocity will limit the momentum generation [29]. Walking at a slower speed has been reported to be more challenging to the motor control system requiring more attention to adapt [30]. Increased MOS variability at the slowest speed was likely related to increased gait variability [13]. Likewise, increased energy expenditure was associated with a faster SWSS, providing additional support that net metabolic power is elevated by increasing speed for both walking and running [31]. This rise is proportional to the work done by leg muscles as speed increased [31].

This study did not come without limitations. Patients with COPD selected a much slower SSWS than the controls ($p=0.001$), likely causing the number of strides to be different between groups. This may have affected the standard deviation calculation. We controlled for speed statistically; yet, it is unknown if this controlled for number of strides. On the other

hand, if we had selected to use the same number of strides for all participants, this may have led to unequal duration of walking for each participant possibly confounding the results due to fatigue. Future studies could increase the number of subjects, allowing for speed-matched comparisons. Additionally, our findings in the AP direction may appear to contradict findings in other pathologies [13, 30]. This is possibly due to 1) the effect of covariates in the current study, 2) the consideration of treadmill speed in the estimation of extrapolated COM, and/or 3) the differences in the definition of the AP limits of the BOS lead to these conflict in results. The speed of treadmill in the AP direction should be added to the speed of the COM to account for the actual momentum of the body in the calculation of extrapolated COM. Furthermore, in the current study, the heel marker was used as the boundary of the BOS as it is closer to the location of the center of pressure at heel strike. Consideration should also be given to the resolution of heel strike detection as slight errors in timing may influence MOS calculations in the AP direction.

In conclusion, patients with COPD may have tried to compensate for their lack of stability by significantly increasing stability margins in the ML direction instead of the AP direction, due to its association with energy expenditure. Patients with COPD have limited metabolic capacity and altering MOS in the AP direction may add to their metabolic demands. To reduce the risk of falls in these patients, there is a need to design training programs to improve dynamic stability and energy expenditure.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors would like to thank the participants, Patrick Meng-Frecker and Casey Wiens for help with data collection, and Will Denton for assistance with analysis. Funding was provided by the National Institutes of Health (P20 GM109090 [J.M.Y.]).

REFERENCES

- [1]. S. National Center for Health, Health, United States, Health, United States, 2015: With Special Feature on Racial and Ethnic Health Disparities, National Center for Health Statistics (US), Hyattsville (MD), 2016.
- [2]. Fabbri LM, Luppi F, Beghe B, Rabe KF, Complex chronic comorbidities of COPD, *Eur Respir J* 31(1) (2008) 204–12. <https://www.ncbi.nlm.nih.gov/pubmed/18166598>. [PubMed: 18166598]
- [3]. Roig M, Eng JJ, MacIntyre DL, Road JD, Reid WD, Associations of the Stair Climb Power Test with muscle strength and functional performance in people with chronic obstructive pulmonary disease: a cross-sectional study, *Phys Ther* 90(12) (2010) 1774–82. <https://www.ncbi.nlm.nih.gov/pubmed/21030661>. [PubMed: 21030661]
- [4]. Crisan AF, Oancea C, Timar B, Fira-Mladinescu O, Tudorache V, Balance impairment in patients with COPD, *PLoS One* 10(3) (2015) e0120573 <https://www.ncbi.nlm.nih.gov/pubmed/25768731>. [PubMed: 25768731]
- [5]. Florence CS, Bergen G, Atherly A, Burns E, Stevens J, Drake C, Medical Costs of Fatal and Nonfatal Falls in Older Adults, *J Am Geriatr Soc* 66(4) (2018) 693–698. <https://www.ncbi.nlm.nih.gov/pubmed/29512120>. [PubMed: 29512120]

- [6]. Roig M, Eng JJ, MacIntyre DL, Road JD, FitzGerald JM, Burns J, et al., Falls in people with chronic obstructive pulmonary disease: an observational cohort study, *Respir Med* 105(3) (2011) 461–9. <https://www.ncbi.nlm.nih.gov/pubmed/20869227>. [PubMed: 20869227]
- [7]. Yentes JM, Rennard SI, Schmid KK, Blanke D, Stergiou N, Patients with Chronic Obstructive Pulmonary Disease Walk with Altered Step Time and Step Width Variability as Compared with Healthy Control Subjects, *Ann Am Thorac Soc* 14(6) (2017) 858–866. <https://www.ncbi.nlm.nih.gov/pubmed/28267374>. [PubMed: 28267374]
- [8]. Annegarn J, Spruit MA, Savelberg HHCM, Willems PJB, van de Boven C, Schols AMWJ, et al., Differences in walking pattern during 6-min walk test between patients with COPD and healthy subjects, *PloS one* 7(5) (2012) e37329–e37329. <https://www.ncbi.nlm.nih.gov/pubmed/22624017> <https://www.ncbi.nlm.nih.gov/pmc/PMC3356256/>. [PubMed: 22624017]
- [9]. Hausdorff JM, Gait variability: methods, modeling and meaning, *J NeuroEng Rehabil* 2005 2, 19. [PubMed: 16033650]
- [10]. Bruijn SM, Meijer OG, Beek PJ, van Dieën JH, Assessing the stability of human locomotion: a review of current measures, *J R Soc Interface* 10(83) (2013) 20120999 <https://www.ncbi.nlm.nih.gov/pubmed/23516062>. [PubMed: 23516062]
- [11]. Hof AL, Gazendam MG, Sinke WE, The condition for dynamic stability, *J Biomech* 38(1) (2005) 1–8. <https://www.ncbi.nlm.nih.gov/pubmed/15519333>. [PubMed: 15519333]
- [12]. Hof AL, The 'extrapolated center of mass' concept suggests a simple control of balance in walking, *Hum Mov Sci* 27(1) (2008) 112–25. <https://www.ncbi.nlm.nih.gov/pubmed/17935808>. [PubMed: 17935808]
- [13]. Hak L, Houdijk H, van der Wurff P, Prins MR, Mert A, Beek PJ, et al., Stepping strategies used by post-stroke individuals to maintain margins of stability during walking, *Clin Biomech (Bristol, Avon)* 28(9–10) (2013) 1041–8. <https://www.ncbi.nlm.nih.gov/pubmed/24200373>.
- [14]. McAndrew Young PM, Wilken JM, Dingwell JB, Dynamic margins of stability during human walking in destabilizing environments, *J Biomech* 45(6) (2012) 1053–9. <https://www.ncbi.nlm.nih.gov/pubmed/22326059>. [PubMed: 22326059]
- [15]. van Meulen FB, Weenk D, van Asseldonk EH, Schepers HM, Veltink PH, Buurke JH, Analysis of Balance during Functional Walking in Stroke Survivors, *PLoS One* 11(11) (2016) e0166789 <https://www.ncbi.nlm.nih.gov/pubmed/27855211>. [PubMed: 27855211]
- [16]. Matsubara JH, Wu M, Gordon KE, Metabolic cost of lateral stabilization during walking in people with incomplete spinal cord injury, *Gait & posture* 41(2) (2015) 646–651. <https://www.ncbi.nlm.nih.gov/pubmed/25670651> <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4318628/>. [PubMed: 25670651]
- [17]. Donelan JM, Kram R, Kuo AD, Mechanical and metabolic determinants of the preferred step width in human walking, *Proc Biol Sci* 268(1480) (2001) 1985–1992. <https://www.ncbi.nlm.nih.gov/pubmed/11571044> <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC108839/>. [PubMed: 11571044]
- [18]. Zarrugh MY, Radcliffe CW, Predicting metabolic cost of level walking, *European Journal of Applied Physiology and Occupational Physiology* 38(3) (1978) 215–223. 10.1007/BF00430080. [PubMed: 648512]
- [19]. Brach JS, Berthold R, Craik R, VanSwearingen JM, Newman AB, Gait Variability in Community-Dwelling Older Adults, *Journal of the American Geriatrics Society* 49(12) (2001) 1646–1650. 10.1111/j.1532-5415.2001.49274.x. [PubMed: 11843998]
- [20]. HOLT KG, HAMILL J, ANDRES RO, Predicting the minimal energy costs of human walking, *Medicine & Science in Sports & Exercise* 23(4) (1991) 491–498. https://journals.lww.com/acsm-msse/Fulltext/1991/04000/Predicting_the_minimal_energy_costs_of_human.16.aspx. [PubMed: 1905381]
- [21]. Yentes JM, Schmid KK, Blanke D, Romberger DJ, Rennard SI, Stergiou N, Gait mechanics in patients with chronic obstructive pulmonary disease, *Respir Res* 16 (2015) 31 <https://www.ncbi.nlm.nih.gov/pubmed/25849481>. [PubMed: 25849481]
- [22]. Yentes JM, Denton W, Samson K, Schmid KK, Wiens C, Rennard SI, Energy efficient physiologic coupling of gait and respiration is altered in chronic obstructive pulmonary disease, *Acta Physiologica* 0(0) (2018) e13217 10.1111/apha.13217.

- [23]. Beauchamp MK, Sibley KM, Lakhani B, Romano J, Mathur S, Goldstein RS, et al., Impairments in Systems Underlying Control of Balance in COPD, *Chest* 141(6) (2012) 1496–1503. <http://www.sciencedirect.com/science/article/pii/S0012369212603390>. [PubMed: 22116798]
- [24]. Global Initiative for Chronic Obstructive Lung Disease. , Global Strategy for the Diagnosis, Management and Prevention of COPD., Gold, 2019.
- [25]. Alexander RM, Models and the scaling of energy costs for locomotion, *Journal of Experimental Biology* 208(9) (2005) 1645 <http://jeb.biologists.org/content/208/9/1645.abstract>. [PubMed: 15855396]
- [26]. Guenette JA, Chin RC, Cheng S, Dominelli PB, Raghavan N, Webb KA, et al., Mechanisms of exercise intolerance in Global Initiative for Chronic Obstructive Lung Disease grade 1 COPD, *European Respiratory Journal* 44(5) (2014) 1177 <http://erj.ersjournals.com/content/44/5/1177.abstract>. [PubMed: 25142487]
- [27]. Bruijn SM, van Dieën JH, Control of human gait stability through foot placement, *J R Soc Interface* 15(143) (2018). <https://www.ncbi.nlm.nih.gov/pubmed/29875279>.
- [28]. O'Connor SM, Kuo AD, Direction-dependent control of balance during walking and standing, *J Neurophysiol* 102(3) (2009) 1411–9. <https://www.ncbi.nlm.nih.gov/pubmed/19553493>. [PubMed: 19553493]
- [29]. Kaya BK, Krebs DE, Riley PO, Dynamic Stability in Elders: Momentum Control in Locomotor ADL, *The Journals of Gerontology: Series A* 53A(2) (1998) M126–M134. 10.1093/gerona/53A.2.M126.
- [30]. Peebles AT, Bruetsch AP, Lynch SG, Huisinga JM, Dynamic balance in persons with multiple sclerosis who have a falls history is altered compared to non-fallers and to healthy controls, *J Biomech* 63 (2017) 158–163. <https://www.ncbi.nlm.nih.gov/pubmed/28889946>. [PubMed: 28889946]
- [31]. Farris DJ, Sawicki GS, The mechanics and energetics of human walking and running: a joint level perspective, *Journal of the Royal Society, Interface* 9(66) (2012) 110–118. <https://www.ncbi.nlm.nih.gov/pubmed/21613286> <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3223624/>.

HIGHLIGHTS

- Mediolateral margin of stability was greater in COPD patients compared to controls
- Dynamic stability contribution to energy expenditure did not differ between groups
- Speed and step width confounded margin of stability findings

Figure 1.
Comparison of the metabolic power for both groups (Healthy controls in black and patients with COPD in gray) and the three walking speed conditions.

Figure 2. Unadjusted anteroposterior (AP; left column) and medio-lateral (ML; right column) margin of stability (MOS) means (top row) and variability (bottom row) for both groups and each walking speed condition. Healthy controls are shown in black and patients with COPD are in gray. NOTE: horizontal bars represent speed differences across groups after adjustment for covariates ($p<0.05$).

Table 1.

Demographic data for the participants used in the analysis. All values are written as mean (standard deviation).
 Note: FEV₁/FVC is Forced expiratory volume in one second/Forced vital capacity

	Controls (n=23)	COPD (n=17)	p-value
Male/Female (n)	5/18	8/9	
Age (years)	59.9 (6.60)	64.3 (7.64)	0.06
Body mass (kg)	73.7 (15.8)	89.7 (31.7)	0.11
Height (m)	1.63 (0.07)	1.67 (0.11)	0.04
FEV₁/FVC (%)	79.1 (5.32)	54.0 (13.7)	<0.0001
SSWS (m/s)	1.10 (0.23)	0.70 (0.30)	0.001
Respiratory Exchange Ratios			
–20%SSWS	0.67(0.15)	0.65(0.14)	0.69
SSWS	0.67(0.15)	0.67(0.14)	0.93
+20%SSWS	0.67(0.14)	0.69(0.16)	0.62
Step width (m)			
–20%SSWS	0.10 (0.03)	0.09 (0.03)	0.45
SSWS	0.11 (0.03)	0.10 (0.03)	0.49
+20%SSWS	0.10 (0.03)	0.09 (0.03)	0.44
Step time (sec)			
–20%SSWS	0.69 (0.20)	0.84 (0.17)	0.03
SSWS	0.57 (0.06)	0.71 (0.14)	<0.0001
+20%SSWS	0.54 (0.06)	0.69 (0.12)	<0.0001
Step length (m)			
–20%SSWS	0.53 (0.08)	0.42 (0.11)	0.002
SSWS	0.55 (0.09)	0.45 (0.13)	0.007
+20%SSWS	0.63 (0.10)	0.52 (0.13)	0.006

Table 2.

Linear mixed models, one for each measure of stability outcome variable.

Model	Variable	Category (vs. Reference)	Coefficient	Coefficient Standard Error	Standardized Coefficient	P-Value	
MOS AP mean Models *							
Subgroup Model: Healthy Controls							
	Intercept		57.59	28.29	-76.17		
	Speed Condition					<.0001	$\ddagger$
		+20%SSWS (vs. SSWS)	-31.70	7.01	-124.11		
		-20%SSWS (vs. SSWS)	63.64	7.01	249.20		
	SSWS		-141.25	26.77	-258.95	<.0001	
Subgroup Model: COPD Patients							
	Intercept		17.39	30.87	-27.10		
	Speed Condition					<.0001	$\ddagger\ddagger$
		+20%SSWS (vs. SSWS)	-8.59	10.40	-28.91		
		-20%SSWS (vs. SSWS)	58.14	10.40	195.73		
	SSWS		-86.98	39.71	-185.58	0.04	
MOS AP variability Model							
	Intercept		24.43	3.02	19.26	<.0001	
	Group					0.26	
		COPD (vs. Controls)	1.92	1.69	10.38		
	Speed Condition					<.0001	$\ddagger\ddagger$
		+20%SSWS (vs. SSWS)	-0.69	0.80	-3.58		
		-20%SSWS (vs. SSWS)	3.11	0.80	16.06		
	SSWS		-7.66	2.77	-25.32	0.01	
MOS ML mean Model							
	Intercept		102.47	7.31	137.10		
	Group					0.02	
		COPD (vs. Controls)	15.41	6.48	83.47		
	Speed Condition					<.0001	$\ddagger\ddagger$
		+20%SSWS (vs. SSWS)	-2.17	1.07	-11.18		
		-20%SSWS (vs. SSWS)	6.57	1.06	33.91		
	Step Width		269.86	56.50	108.30	<.0001	

Model	Variable	Category (vs. Reference)	Coefficient	Coefficient Standard Error	Standardized Coefficient	P-Value		
MOS ML variability Model								
	Intercept		9.50	1.38	13.61			
	Group					0.07		
		COPD (vs. Controls)	1.81	1.00	9.80			
	Speed Condition					0.003	†††	
		+20%SSWS (vs. SSWS)	0.58	0.31	2.97			
		-20%SSWS (vs. SSWS)	1.07	0.30	5.51			
	Step Width		28.42	11.50	11.40	0.02		

* The MOS AP Mean model had a significant interaction between group and speed condition ($p = 0.048$), so a subgroup analysis was run where separate linear mixed models were fit for the COPD patients and healthy controls.

† All three speed conditions significantly differ from each other (adjusted p 's < 0.001).

†† The slow condition significantly differs from the fast and PWS conditions (adjusted p 's < 0.001).

††† The slow condition significantly differs from the PSW condition (adjusted $p = 0.002$).

Table 3.

Linear mixed models, one for each measure of stability predictor, with metabolic power as the outcome.

Model	Variable	Group (vs. reference)	Model Coefficient	Standard Error	Standardized Coefficient	P-Value	
Outcome: Metabolic Power							
	Intercept		1.75	0.55	2.78		
	SSWS (m/s)		0.63	0.54	2.08	0.25	
	Group					0.98	
		COPD (vs. Controls)	-0.01	0.31	-0.04		
	Speed Condition					0.01	^
		+20%SSWS (vs. SSWS)	0.32	0.11	1.63		
		-20%SSWS (vs. SSWS)	-0.08	0.14	-0.41		
	MOS AP mean		-0.007	0.002	-5.29	<.0001	
Outcome: Metabolic Power							
	Intercept		0.71	0.65	2.78		
	SSWS (m/s)		1.70	0.52	5.61	0.002	
	Group					0.58	
		COPD (vs. Controls)	-0.18	0.31	-0.95		
	Speed Condition					<.0001	†
		+20%SSWS (vs. SSWS)	0.50	0.11	2.57		
		-20%SSWS (vs. SSWS)	-0.63	0.12	-3.27		
	MOS AP variability		0.036	0.014	2.43	0.01	
Outcome: Metabolic Power							
	Intercept		1.39	0.89	2.78		
	SSWS (m/s)		1.42	0.52	4.71	0.01	
	Group					0.70	
		COPD (vs. Controls)	-0.13	0.32	-0.68		
	Speed Condition					<.0001	†
		+20%SSWS (vs. SSWS)	0.48	0.11	2.47		
		-20%SSWS (vs. SSWS)	-0.53	0.12	-2.73		
	MOS ML mean		0.001	0.005	0.39	0.78	
Outcome: Metabolic Power							
	Intercept		1.40	0.68	2.78		
	SSWS (m/s)		1.43	0.51	4.74	0.01	
	Group					0.69	
		COPD (vs. Controls)	-0.13	0.32	-0.68		

Model	Variable	Group (vs. reference)	Model Coefficient	Standard Error	Standardized Coefficient	P-Value	
	Speed Condition					<.0001	[†]
		+20% SSWS (vs. SSWS)	0.47	0.11	2.41		
		-20% SSWS (vs. SSWS)	-0.53	0.12	-2.76		
	MOS ML variability		0.014	0.029	0.54	0.63	

[^] The fast speed condition has higher power than the PWS condition (adjusted p=0.01).

[†] All speed conditions significantly differ from each other (adjusted p's<0.001).