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REVIEW

Updated Perspectives on the Role of Biomechanics in COPD: Considerations for the Clinician

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Abstract: Patients with chronic obstructive pulmonary disease (COPD) demonstrate extra-pulmonary functional decline such as an increased prevalence of falls. Biomechanics offers insight into functional decline by examining mechanics of abnormal movement patterns. This review discusses biomechanics of functional outcomes, muscle mechanics, and breathing mechanics in patients with COPD as well as future directions and clinical perspectives. Patients with COPD demonstrate changes in their postural sway during quiet standing compared to controls, and these deficits are exacerbated when sensory information (eg, eyes closed) is manipulated. If standing balance is disrupted with a perturbation, patients with COPD are slower to return to baseline and their muscle activity is differential from controls. When walking, patients with COPD appear to adopt a gait pattern that may increase stability (eg, shorter and wider steps, decreased gait speed) in addition to altered gait variability. Biomechanical muscle mechanics (ie, tension, extensibility, elasticity, and irritability) alterations with COPD are not well documented, with relatively few articles investigating these properties. On the other hand, dyssynchronous motion of the abdomen and rib cage while breathing is well documented in patients with COPD. Newer biomechanical technologies have allowed for estimation of regional, compartmental, lung volumes during activity such as exercise, as well as respiratory muscle activation during breathing. Future directions of biomechanical analyses in COPD are trending toward wearable sensors, big data, and cloud computing. Each of these offers unique opportunities as well as challenges. Advanced analytics of sensor data can offer insight into the health of a system by quantifying complexity or fluctuations in patterns of movement, as healthy systems demonstrate flexibility and are thus adaptable to changing conditions. Biomechanics may offer clinical utility in prediction of 30-day readmissions, identifying disease severity, and patient monitoring. Biomechanics is complementary to other assessments, capturing what patients do, as well as their capability.

Keywords: kinematics, kinetics, postural control, mechanomyography, balance, wearables

Introduction

Chronic obstructive pulmonary disease (COPD) is not strictly a disease of the lungs. Extrapulmonary consequences prominently include muscle fatigue,[1] muscle weakness[2] and increased fall risk, which are often major patient concerns, as well as dysfunction of many other organ systems. Potential physiological explanations for alterations in skeletal muscle physiology include atrophy, fiber type shifting, mitochondrial loss and/or dysfunction, and structural changes[3–8] (Figure 1). Further, patients with COPD (PwCOPD) demonstrate drastic extra-pulmonary functional decline that progresses with disease severity that may be independent of decline in lung function.[9] Functional outcomes can be measured in a variety of ways. In particular, the scientific study of human movement, kinesiology, is an overarching umbrella that contains the disciplines of exercise physiology, motor control/learning, motor development, and biomechanics. In this context, functional exercise capacity, peripheral muscle strength, gait/mobility, balance, and physical activity, parameters within the scope of biomechanics, are all affected in PwCOPD.[2,10–17]

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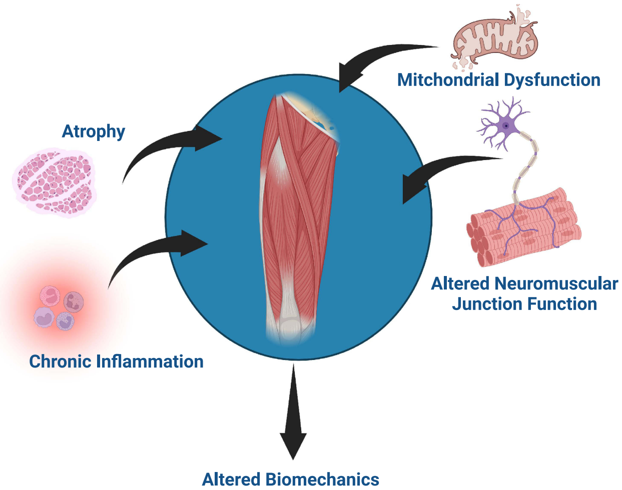

Figure 1 Simplified depiction of COPD pathophysiology that leads to biomechanical alterations. Mitochondrial loss/dysfunction, increased circulating inflammatory cells, muscle atrophy, and alterations at the neuromuscular junction contribute to decreased muscle force, rate of force generation, and physical activity, as well as increased muscle fatigue and weakness. These factors, along with many others, contribute to altered biomechanics, decreased exercise capacity, increased physical inactivity, and exercise intolerance. Created with BioRender.com.

What is Biomechanics?

Biomechanics is defined as the scientific study of forces that act upon a body and the reactions produced. In essence, it represents "the broad interplay between mechanics and biological systems".[18] Biomechanical investigations span whole-body to tissue-level mechanics. Biomechanical areas of interest include clinical, engineering, imaging and material properties, models and robotics, sports, and animal mechanics. Clinical biomechanics, in particular, investigates injury, pathology, prosthetics, and rehabilitation. The application of biomechanics to clinical questions is extensive. Clinical research using biomechanics has included observation, diagnosis, monitoring, and rehabilitation.

Laboratory-based biomechanical analyses could be considered the microscope of movement, with accuracies of < 1 mm. Common tools or methods include the use of motion capture (kinematics), force platforms (kinetics), accelerometers, inertial measurement units, computerized dynamometers, and ultrasound (Figure 2). Motion capture is used to record where the body is in space. Using small, retroreflective markers, one can identify exactly how the body is positioned and how fast it is moving. Motion capture is used to calculate joint angles, acceleration of a limb, or even gait speed. Force platforms are used to measure the amount of force exerted by the body in three directions: vertical (synonymous with body weight when standing still), and anteroposterior and mediolateral directions (both shear forces). Force data in combination with motion capture data can provide information about torque, work, and power done at each joint. Inertial measurement units include an accelerometer, gyroscope, and magnetometer. They are found in smart phones and watches, as well as other wearables and are used for step counts and activity monitoring. In cases when motion capture is not available, they have been used to estimate body position. The most commonly known dynamometer is the hand grip dynamometer that provides a reading of grip strength. A computerized dynamometer is similar in that it will provide muscular strength or endurance information for nearly any joint. Depending on the settings, isotonic (ie, concentric or eccentric), isometric, or isokinetic strength and endurance can be tested. Rate of force production, work, and other useful measures of muscular performance can also be measured. The use of an ultrasound provides further information about the muscular tissue itself such as fascicle length and velocity as well as pennation angle (defined in Table 1).

Other techniques such as electromyography and mechanomyography have been used as well. Electromyography measures the electrical activity present during a muscle contraction. Both surface and fine-wire electromyography can be used. Surface is the most common as this uses electrodes to read the summation of electrical activity at a muscle belly. Fine-wire or intramuscular electromyography can record electrical activity of deep musculature and provide recordings of single muscle activity. Mechanomyography has been used to identify mechanical activation of muscle tissue[19,20] rather than electrical activation. Typically using a microphone, the movement or displacement of a muscle can be identified.

Figure 2 Typical biomechanical methods. (**A** and **B**) Motion capture represented by cameras systems in the background (solid red circle) record where markers are in space (dotted red circle) and provide information about where the person is in space (kinematics). (**C**) Force platforms provide information about forces (kinetics). (**D**) Dynamometers provide information regarding muscle strength and power.

All of the methods mentioned are typically combined with techniques from physiology such as measurement of oxygen consumption, bioelectrical impedance, and electrocardiography. In addition to traditional tools, technological improvements have allowed for the use of brain activation tools to be used during movement such as functional near-infrared spectroscopy and electroencephalography.

Starting in the last century, biomechanics focus began to be given to breathing mechanics in COPD such as force generating capacity of musculature.[21] This expanded into investigations of functional outcomes in COPD such as muscle fatigue,[1,22] balance,[15] falling,[23,24] and gait.[14,25] There has even been an investigation in to the biomechanics of swallowing in PwCOPD.[26] The purpose of this manuscript is to review the current knowledge regarding biomechanics in COPD and how this can be applied clinically. The status of literature regarding functional outcomes, muscle mechanics, and breathing mechanics are reviewed as well as future directions and clinical perspectives.

Functional Outcomes

Balance

Fall rates vary among older adults according to age. However, it is estimated that 30% of persons over the age of 65 years fall each year, and this percentage increases up to 50% among people over 80 years.[27,28] Early studies identified an

Table 1 Definitions of Biomechanical Terms

Term	Definition	Implication
Fascicle length	"distance between the intersection of the fascicle with the superficial and deeper aponeurosis"[172]	Length is a function of the number of in series sarcomeres; considered by some as the single most important architectural parameter of a muscle affecting its function
Fascicle velocity	Time derivative of fascicle length	Increased fascicle shortening velocity is associated with an increased rate of force development
Muscle contractility	Ability to contract	Paralysis is the inability to contract muscle tissue
Muscle elasticity	Ability to recoil after being stretched	Allows the muscle to return to its normal shape
Muscle extensibility	Ability of the muscle to be stretched	A lack of extensibility would be spasticity
Muscle irritability (also known as excitability)	Ability to respond to a stimulus	Rippling muscle disease is a condition in which muscles are unusually hyperexcitable
Muscle stiffness	Change in force divided by the corresponding change in length or resistance of muscle to length change	Limits excessive joint motion or translation after a perturbation
Muscle tension	Force generated by a contracting muscle	Amount of tension (force) a muscle can produce is dependent upon the number of cross-bridges formed between actin and myosin
Pennation angle	Muscle fiber architecture; the angle between fiber orientation and the longitudinal axis of the bone	The greater a pennation angle provides a mechanical advantage, the more force can be generated in the muscle
Shear wave elastography	Produces "an acoustic radiofrequency force impulse, which generates transversely-oriented shear waves that propagate through the surrounding tissue and provide biomechanical information about tissue quality"[173]	Quantifies mechanical and elastic properties of skeletal muscle tissue
Stretch-shortening cycle	Active stretching of a muscle before active contraction. Sometimes referred to as "pre-stretch" or "countermovement"	Storage of elastic energy. Resulting force, work, and power are enhanced with an active pre-stretch

increase in fall risk and deficiencies in balance control in PwCOPD.[23,24,29–32] PwCOPD are 55% more likely to have a record of a fall compared to those without COPD,[33] with an estimated prevalence of COPD fallers at 30%.[34] Early evidence suggests that those with a bronchitic COPD phenotype are more likely to have poorer balance (shorter single limb stance time) and higher fall risk (longer time to complete the Timed Up and Go test) compared to those with an emphysematous phenotype.[35] PwCOPD experiencing an acute disease exacerbation are likely to fall more and demonstrate balance impairments beyond those with stable disease.[36] Previous literature reviews reported that balance deficiencies in COPD were related to increases in age, muscle weakness, physical inactivity, and use of supplementary oxygen and related to a decrease in exercise capacity.[37,38] Number of medications, restriction of recreational activities, anxiety, and depression are also related to worse balance scores in PwCOPD.[39,40] A deficiency in the production of rapid force (ie, vertical jump) has been related to the number of self-reported falls in PwCOPD.[41]

Postural control deficits in PwCOPD compared to those without COPD include changes in sway while quietly standing[16,42–46] (Table 2). Sway is typically quantified through static posturography (ie, standing on force platform while measuring a person's sway). Every person has a natural sway when standing, and sway naturally increases when a person closes their eyes when standing. PwCOPD have greater total sway displacement[16] —greater amount of sway—compared to controls. Specifically, sway in the mediolateral direction has been found to discriminate between PwCOPD and those without COPD.[45,47] Both slower sway velocity[11,43] and faster sway velocity in the anteroposterior direction[44] have been reported in PwCOPD. Currently, in PwCOPD, it is unclear as to how velocity or speed of sway is related to postural control and/or the risk of future falls.

Table 2 Studies of Balance in PwCOPD That Used Biomechanical Measures of Postural Sway

Study	Subjects	Conditions	Dependent Variables	Results
Silva Almeida, et al[43]	14 PR PwCOPD 9 controls	EO, EC, ECF, EO with respiratory overload	COP area COP displacement COP variability COP velocity	Increased COP area and displacement, variability in ML, velocity in AP compared to controls
Butcher, et al[15]	30 PwCOPD 21 controls	SOT	Sway magnitude Peak sway displacement	Increased COP sway magnitude and displacement during test 3, EO and platform tilted anteriorly and posteriorly compared to controls
Costa Boffino, et al[174]	30 PwCOPD 30 OA controls 30 YA controls	Modified SOT	COP amplitude COP variability COP velocity	Increased COP amplitude, variability, and velocity compared to OA and YA controls
de Castro, et al[54]	33 PwCOPD 33 controls	EO, EC, EOF, OLS	COP area COP velocity EMG	Increased COP area and velocity of AP and ML during OLS, with higher activation of scalenes compared to controls
de Castro, et al[16]	47 PwCOPD 25 controls	OLS	COP area COP velocity	Increased COP area compared to controls
de Castro, et al[175]	31 PwCOPD completed 3 mo. land or water exercise program	EO, EC, EO feet together, OLS	COP area	No differences
Eymir, et al[42]	24 PwCOPD 24 controls	Biodex balance system	Stability index	Worse postural stability overall and in both AP and ML directions compared to controls.
Gloeckl, et al[48]	48 PR PwCOPD with whole-body vibration training or conventional balance training	EC, OLS, Semi-tandem stance with EC	Absolute path length	Whole-body vibration group had a greater change in absolute path length in semi-tandem stance and OLS compared to conventional balance group
Janssens, et al[46]	20 PwCOPD 20 controls	ECF w/ and w/o muscle vibration	COP RMS	Increased sway in AP compared to controls Increased reliance on ankle proprioceptive signals, lower reliance on back muscle signals compared to controls
Jirange, et al[11]	42 PwCOPD 45 controls	EO, EC, EOF, ECF	COP velocity COP velocity moment	During EO, velocity in AP was faster and velocity moment was increased in COPD During EC, velocity in AP and ML was faster in COPD compared to controls No results given for foam condition

(*Continued*)

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Table 2 (Continued).

Study	Subjects	Conditions	Dependent Variables	Results
Molouki, et al[47]	15 PwCOPD 14 controls	EO, EC, EO & EC with counting task	COP variability COP velocity COP variability of velocity Lyapunov exponent	PwCOPD had greater COPD variability of sway and velocity, and Lyapunov exponents compared to controls across all conditions
Oliveira, et al[36]	26 PwCOPD & exacerbation 26 stable PwCOPD 25 controls	EO, EC, EOF, EO feet together	COP path length COP amplitude	Those experiencing exacerbations performed worse than controls for most variables in all conditions Only during EOF did stable COPD perform worse than controls
Park, et al[44]	34 PwCOPD 22 controls	EO	COP velocity COP displacement COP area	Increased AP velocity compared to controls
Porto, et al[52]	93 PwCOPD 39 controls	Tetrax (8 conditions)	COP sway	No difference
Roig, et al[30]	20 PwCOPD 20 controls	SOT	Equilibrium score (amount of sway)	During conditions when only vestibular systems were useful for postural control were there differences between PwCOPD and controls
Smith, et al[45]	12 PwCOPD 12 controls	EO, EC, EOF, EO short base	COP max amplitude COP RMS	PwCOPD had greater RMS in ML during all conditions and greater max amplitude in ML when standing on foam
Smith, et al[53]	15 PwCOPD 15 controls	EO with perturbation (rapid shoulder flexion/extension) before and after arm ergometry exercise	COP displacement COP velocity	PwCOPD took longer to return to baseline after perturbation and did not always return to baseline in AP direction Exercise had no effect
Van Hove, et al[49]	21 PwCOPD 21 controls	EO, EC, EO & EC with cognitive tasks (serial 3 subtraction, category fluency)	COP displacement COP area COP range COP variability COP velocity	PwCOPD had worse balance than controls Addition of cognitive tasks mainly affected speed related measures

Abbreviations: EO, eyes open; EC, eyes closed; F, Foam; OLS, one-legged stance; COP, center of pressure; ML, mediolateral; AP, anteroposterior; PR, pulmonary rehabilitation; SOT, sensory organization test; OA, older adults; YA, young adults; RMS, root mean square.

These differences in sway are exacerbated when sensory information is disrupted such as closing their eyes, standing on foam, or vibrations applied at the ankle joint.[13,15,36,43,45,46] The greatest differences in postural control between PwCOPD and controls were found when both vision and proprioception were manipulated.[30] On the other hand, additional sensory information may be helpful in rehabilitation and improvement of postural control. PwCOPD that underwent whole-body vibration training for three weeks, demonstrated changes in postural sway compared to those that underwent conventional balance training.[48] As opposed to sensory manipulations, no influence of an additional cognitive load while standing was found on standing postural control.[49]

Caution is needed when interpreting findings of sway. Many studies conclude that decreased sway with less variability is reflective of a better postural control. However, a restrictive sway, very small sway displacement and little variability, can also indicate an unhealthy state as seen in stroke survivors and persons with Parkinson's disease.[50,51] This restrictive sway is typically employed to stabilize the head and vision to compensate for other symptoms. Therefore, research studies asking subjects to stand as still as possible could provide misleading results. Changes in sway of either direction (more or less) from controls could be considered poor postural control. The authors define healthy sway as a quasi-stable state with variability in all directions, within limits.

Dynamic activities may affect balance in patients with COPD, along with a higher incidence of falls, compared to controls.[52] This is likely as control of the trunk is important for dynamic postural stability. Using balance perturbations (ie, quick shoulder flexion and extension movements), PwCOPD took longer to return to pre-perturbation velocity of sway in the anteroposterior direction, and those with more severe disease had differential abdominal muscle activity (increased external oblique and rectus abdominis both at baseline and after the perturbation) compared to controls and those with less severe disease.[53] This indicates a challenge of the trunk musculature to balance both respiration and control of the trunk in PwCOPD. Similar findings have been reported in which higher muscle activation of the scalenes along with greater sway velocity was recorded during one-legged standing in PwCOPD compared to controls.[54] The increased respiratory demand in PwCOPD may alter the typical biomechanical role of these muscles in postural control, possibly underpinning the balance alterations in these patients. This study also reported no difference in sway performance between PwCOPD and controls when standing with eyes open, eyes closed, or on an unstable surface. However, the gluteus medius did demonstrate a higher activation in PwCOPD during standing with eyes closed, potentially indicating a higher reliance on a hip strategy during eyes closed. Trunk symmetry in the mediolateral direction was more asymmetrical in PwCOPD and was correlated with the amount of time patients could stand on one leg.[55] PwCOPD have been found to require more time during a stand-to-sit task compared to a sit-to-stand task.[56] The stand-to-sit requires greater postural control of the trunk to successfully complete the task, demonstrating another way in which control of balance has been shown to be challenged in PwCOPD (Table 3).

Gait

Walking is an important characteristic of many instrumental activities of daily living. An important functional measure of gait is its speed.[57] In older adults, a higher risk of mortality, mobility limitation, mobility disability (eg falling), and cardiovascular disease was associated with taking longer to complete 400 m of walking.[58,59] Gait speed has been associated with survival in older adults,[60] hospitalization,[61] and disability.[62] In PwCOPD, gait speed slows with disease severity,[63] and is moderately associated with lung function, dyspnea, quality of life, muscle strength, and physical activity.[64,65] Gait speed at hospital discharge is a way to identify PwCOPD at risk for readmission.[66] Moreover, it is possible that pulmonary rehabilitation will improve gait in PwCOPD.[67,68]

Despite the importance of walking, there is a dearth of studies using biomechanical tools to investigate gait patterns in PwCOPD. It is currently unclear as to the magnitude of gait deficiencies associated with the pathophysiology of COPD and whether or not these gait deficiencies are related to fall risk.[69] Further, it is unknown if gait deficiencies associated with COPD are more or less severe than those associated with other diseases. One such study suggests that gait deficiencies in COPD are not as severe as those associated with peripheral artery disease.[70]

Due to the higher risk of falls in PwCOPD, there has been interest in investigating dynamic stability during walking. Potentially to increase stability during walking, PwCOPD walk with increased step time, shorter steps, and wider steps[65,71,72] (Table 4). Ankle kinetics (ie, generating torque and absorbing power) is reportedly affected in PwCOPD

Table 3 Studies of Balance in PwCOPD Using Non-Biomechanical Tests

Study	Subjects	Conditions	Findings
Beauchamp, et al[24]	23 PwCOPD fallers 16 PwCOPD non-fallers	BBS ABC scale TUG	Poorer performance on the BBS, less confidence as reported on the ABC, and longer time to complete TUG in fallers compared to non-fallers
Chauvin, et al[176]	34 PwCOPD fallers 38 PwCOPD non-fallers	BESTest	Balance subcomponent that could identify fallers from non-fallers was stability limits/verticality
Jácome, et al[40]	49 mild PwCOPD 63 moderate PwCOPD 48 severe PwCOPD	TUG	Those with severe to very severe disease took significantly longer to complete the TUG compared to moderate and mild disease Compared to reference values, those aged 70+ took longer to complete the TUG
Janssens, et al[56]	18 PwCOPD 18 controls	EC Sit-to-Stand-to-Sit	Required 46% more time to complete five sit-to-stand-to-sit due to longer stand and stand-to-sit phases
Voica, et al[35]	13 Emphysematous PwCOPD 14 Bronchitic COPD 17 controls	ABC BBS TUG SLS	All COPD had worse balance compared to controls Bronchitic PwCOPD had less confidence (lower ABC), shorter single leg stance times, took longer to complete the TUG compared to emphysemateous PwCOPD
Tudorache, et al[9]	22 stable PwCOPD 19 PwCOPD & exacerbation 20 controls	FES BBS TUG SLS	All COPD had worse balance compared to controls Balance was worse for those experiencing exacerbation compared to those with stable COPD for all measures

Abbreviations: BBS, Berg Balance Scale; ABC, Activity-specific balance confidence scale; TUG, Timed Up and Go; SLS, Single limb stance time; FES, Falls efficacy scale.

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Table 4 Studies of Gait in PwCOPD

Study	Subjects	Conditions	Dependent Variables	Results
Annegarn, et al[75]	79 PwCOPD 24 controls	6MWT	Cadence (strides/min) Inter-stride trunk acceleration variability (autocorrelation)	PwCOPD had a slower cadence and increased variability for medio-lateral acceleration of the trunk compared to controls
Butcher, et al[15]	30 PwCOPD (15 w/ oxygen, 15 w/o) 21 controls	10-meter walk	Fast gait speed from middle 6-meters	PwCOPD and using oxygen have a slower fast gait speed compared to those not using oxygen and controls
Fallahtafti, et al[73]	17 PwCOPD 23 controls	6-minutes of walking on treadmill at 3 speeds	Gait stability Cost of transport	PwCOPD walk with wider stability margins in the ML direction and have less metabolic power than controls
Heraud, et al[83]	25 PR PwCOPD 20 controls	15 min of walking with and without a cognitive task (serial 3 subtraction)	Gait speed Stride time variability	Both groups walked slower during the cognitive task Stride time variability did not differ during walking only; however, was greater during the cognitive task in PwCOPD No effect of PR on dual task performance
Iwakura, et al[65]	34 male PwCOPD 16 male controls	10-meter walk	Gait speed Step length Cadence Walk ratio Step time variability Acceleration magnitude	PwCOPD had slower gait speed and cadence, shorter step lengths, and greater step time variability compared to controls PwCOPD had a decreased acceleration magnitude compared to controls
Jirange, et al[11]	42 PwCOPD 45 controls	Win-Track gait analyzer	Step duration Gait cycle duration Swing duration Step length Gait cycle duration	Swing duration was longer in PwCOPD compared to controls
Karpman, et al[177]	130 PwCOPD	8-meter walk	4-meter usual gait speed 4-meter fast gait speed Physical activity 6MWT	Gait speed is independently associated with 6MWT distance but not physical activity
Lahousse, et al[63]	196 PwCOPD 898 controls	GAITRite mat under normal walk, turn, and tandem walk	Global gait Rhythm Pace Variability	PwCOPD and disease severity were associated with taking slower steps (rhythm)
Liu, et al[12]	80 PwCOPD 38 controls	6MWT on treadmill (GRAIL)	Mean and variability of spatiotemporal measures	PwCOPD had longer duration of strides and decreased stride and step lengths Stride length variability was greater in PwCOPD

(*Continued*)

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Table 4 (Continued).

Study	Subjects	Conditions	Dependent Variables	Results
Liu, et al[67]	44 PR PwCOPD	6MWT on treadmill (GRAIL)	Variability of spatiotemporal measures Gait fluctuation	PR patients were divided into good and poor responders to PR Good responders had longer stride length and shorter stride times Fluctuations in gait did not change
Liu, et al[81]	22 PwCOPD 22 controls	3 minutes of treadmill walking at 3 speeds	Variability and fluctuations of joint angles and range of motion	Controls had more organized fluctuations of hip and knee joint Controls adapted to speed changes compared to PwCOPD
McCamley, et al[70]	16 PwCOPD 25 patients with peripheral artery disease 25 controls	Overground walking at self-selected speed	Kinematic and kinetic gait variables	No significant difference was found between controls and PwCOPD Patients with peripheral artery disease did have differences compared to PwCOPD and controls
McCrum, et al[74]	12 PR PwCOPD 12 controls	Treadmill walking with forward perturbations	Gait stability	No apparent change in gait stability following a forward perturbation
Morlino, et al[13]	40 PwCOPD 28 controls	GAITRite mat	Mean spatiotemporal Variability of step length, duration, and width	Slower cadence and speed, and shorter step length in PwCOPD Variability of step length was greater in PwCOPD
Nantsupawat, et al[25]	14 PwCOPD	6- to 10-meter walk	Spatiotemporal variables	Compared to published norms, PwCOPD had shorter steps, slower cadence, slower walking speed, and spent more time in double support
Sanseverino, et al[82]	11 PwCOPD 11 controls	Cardiopulmonary exercise test across 6 speeds	Walking speed Stride frequency variability	PwCOPD had a slower self-selected walking speed. Only at −40% and +20% of self-selected speed did gait variability differ between groups; however, this difference was gone when compared at isovelocity
Saraiva, et al[79]	36 PwCOPD 19 controls	6MWT	Minimum, mean, and maximum gait speed	Mean and max speeds were slower in PwCOPD
Terui, et al[55]	16 PwCOPD 26 controls	10-minute walk	Trunk acceleration symmetry	PwCOPD demonstrate greater asymmetry of trunk acceleration when walking
Yentes, et al[68]	7 PwCOPD	Overground walking at self-selected speed before and after exercise intervention	Kinematic and kinetic gait variables	Step width decreased following a 6-week exercise intervention
Yentes, et al[72]	17 PwCOPD 21 controls	Overground walking at self-selected speed before and after an acute exercise bout	Kinematic and kinetic gait variables	Ankle kinetics are altered in PwCOPD PwCOPD walk with a wider step width
Yentes, et al[71]	20 PwCOPD 20 controls	3 minutes of treadmill walking at 3 speeds	Step length, time, width variability and fluctuations (sample entropy)	PwCOPD have longer step times and greater variability of step time PwCOPD have a narrower step width and greater variability that is exacerbated with increased gait speed
Yentes, et al[146]	17 PwCOPD 23 controls	6 minutes of treadmill walking at 3 speeds	Locomotor respiratory coupling	PwCOPD have a more rigid coupling that is associated with increased energy expenditure

Abbreviations: 6MWT, six minute walk test; AP, anteroposterior; ML, mediolateral; PR, pulmonary rehabilitation.

compared to controls.[72] PwCOPD walk with larger margins of stability compared to healthy controls, meaning that in the mediolateral direction, they have a wider lateral foot placement (from the extrapolated center of mass) compared to aged-matched controls.[73] Specific, acute, walking-based, stability training appears to modify step behavior, and possibly gait stability outcomes.[74]

The six-minute walk test (6MWT) has been considered an important functional outcome in PwCOPD.[10] It has been used as a surrogate for peak oxygen uptake, aerobic endurance, and exercise capacity. During a 6MWT, PwCOPD walked with slower cadence (ie, strides/min) and increased trunk acceleration variability (ie, increased between-stride time variability) compared to controls[75] as well as altered electromyography of the locomotor muscles.[76] However, it should be considered that the 6MWT differs depending on the length of the walking track,[77] if the subject can rest as long and as much as they want during the test,[78] and if the test involves turns—a biomechanically different task from walking and a task that can take significant time to complete.[79] To mitigate these issues, research has been conducted on completing the 6MWT on a treadmill combined with virtual reality with similar gait deficits reported in other studies.[12,67] However, there are limitations to this approach as walking on a treadmill may alter muscle activation and gait as compared to walking overground. Though virtual reality might address this issue by providing optic flow and a more realistic environment to the patient.

The variability of movement is an important outcome measure regarding health and disease status.[80] As Frey[80] has identified, there is a functional variability between movements with health representing a mid-zone between those that are too rigid or those that have lost control. When walking, PwCOPD demonstrated less control, or less consistent, hip and knee joint movement patterns, especially at faster speeds.[81] Step time and step width variability was altered in PwCOPD,[71] as well as step length.[13] Stride frequency variability, as measured by the coefficient of variation, was increased in PwCOPD as compared to controls at speeds faster and slower than their self-selected walking speed; however, these group differences were not found when speed was controlled.[82] When performing a cognitive task while walking, stride time variability was significantly increased in PwCOPD compared to controls.[83]

Muscle Mechanics

The biomechanical analysis of muscle tissue is typically focused on the contractile and elastic components of the sarcomere. The four biomechanical properties of muscle tissue include tension, extensibility, elasticity, and irritability (for definitions, see Table 1). Much of the work published on muscle dysfunction in COPD has focused on physiology of muscle tissue. There is a paucity of literature focused on biomechanical properties of muscle tissue in COPD (Table 5).

To produce a similar relative force as healthy controls, PwCOPD required a higher stimulation frequency of the vastus lateralis, yet the contractile properties, when corrected for muscle cross sectional areas, were preserved in those with COPD.[84] This is in agreement with other studies.[85] Recent research has reported decreased muscle stiffness and viscosity during passive flexion and extension of the knee.[86] Muscle stiffness of the quadriceps, measured by shear wave elastography (for definition, see Table 1), is decreased in PwCOPD and is inversely associated with lung function, exercise tolerance, muscle strength, and dyspnea.[87] Unlike the quadriceps, muscle stiffness as measured by shear wave velocity has been found to be increased in the diaphragm, indicating a higher muscle stiffness.[88] The stretch-shortening cycle of the vastus lateralis showed higher potentiation in PwCOPD compared to those without.[89] This was also inversely associated with muscle thickness, pennation angle, and habitual gait speed. Smaller pennation angles and reduced muscle thickness have been reported in PwCOPD compared to healthy men.[90]

The altered biomechanical properties of skeletal muscle could lead to increased energy expenditure, decreased force production, and/or abnormal joint motion. They are possible mechanisms for decreased gait speed, increased fatigue, altered gait kinematics, and increased fall risk in PwCOPD. These findings support many of the physiological studies demonstrating abnormalities in the skeletal muscle tissue in PwCOPD. The availability of biomechanical measures could facilitate the development of therapeutic interventions designed to address these issues.

Breathing Mechanics

Changes in relative movement of the abdomen and rib cage are critically important to breathing mechanics. Muscles of the rib cage and abdomen work in coordination to assist the diaphragm in healthy adults, even when the work load is minimal.[91,92]

Table 5 Studies of Muscle Mechanics in PwCOPD

Study	Subjects	Conditions	Dependent Variables	Findings
Casabona, et al[178]	10 PwCOPD 10 controls	Flexion/extension of the knee	EMG amplitude, mean and median frequencies	PwCOPD have less amplitude of activity in extension but not flexion movements compared to controls Frequencies were higher in PwCOPD compared to controls Frequency was correlated with disease severity
Navarro-Cruz, et al[89]	26 PwCOPD 10 physically active controls	Leg press exercise	4-meter gait speed Vastus lateralis muscle thickness, pennation angle, fascicle length Force-velocity relationship	PwCOPD had a slower gait speed The stretch-shortening cycle-induced potentiation was higher in PwCOPD The stretch-shortening cycle-induced potentiation was associated with slower gait speed, less muscle thickness, and smaller pennation angles
Sariabous, et al[117]	13 PwCOPD 7 controls	Quiet breathing an incremental ventilatory effort protocol	Inspiratory mouth pressure Respiratory muscle MMG Efficiency of inspiratory muscle activation	Increases in COPD severity was associated with increases in muscle activation Efficiency of muscle activation was lower in PwCOPD and decreased with severity
Valle, et al[86]	11 PwCOPD 11 controls	Passive leg oscillations (pendulum test)	EMG Viscosity and stiffness coefficients	PwCOPD had less EMG activation PwCOPD had lower viscosity and stiffness values compared to controls

Abbreviations: EMG, electromyography; MMG, mechanomyography.

This is not the case in PwCOPD. Early results demonstrated that dyssynchronous thoracoabdominal motion, "suggesting ineffective diaphragmatic function", is associated with disease severity in COPD.[93] Exercise appears to change thoracoabdominal motion in persons with airway obstruction[94,95] (Table 6). Arm exercise, whether unsupported arm lifts or arm cycle ergometry, led to dyssynchronous breathing.[96,97] In PwCOPD, unsupported arm exercise yet not leg cycling, induced dyssynchronous breathing, which was associated with dyspnea.[98] However, during leg cycling exercise in PwCOPD, an increased percent contribution of abdominal motion to tidal volume was greater than the increased percent contribution of ribcage motion. Abdominal motion continued to contribute a greater percentage to tidal volume as exercise workload increased.[99] Moreover, dyssynchronous thoracoabdominal motion (ie, less rib cage excursion and increased abdominal excursion in PwCOPD compared to controls) impacts clinical outcomes such as the 6MWT in PwCOPD.[100] Rib cage excursion independently predicted the distance walked during the 6MWT and further, rib cage excursion was inversely related to lung hyperinflation.[100] Hyperinflation, in turn, may be either static, resulting from reduced lung elastic recoil and alterations in the chest wall, or dynamic, resulting from the inability of the lungs to deflate fully due to reduced expiratory airflows.[101] The degree to which dyssynchronous breathing impacts hyperinflation is not established. Finally, hyperinflation can be addressed by both pharmacologic and surgical approaches.[102] Understanding the contribution of biomechanical dysfunction to these processes will be important to optimize these treatments.

Optoelectronic plethysmography (OEP) using motion capture to record breathing mechanics based upon movement of the thorax and abdomen was first introduced in 1999.[103] Chest wall kinematics are directly measured from this technique[104] and regional compartmental volumes can be accurately estimated.[105,106] End-expiratory lung volume[107] and inspiratory capacity[108] measured from OEP are valid against gold standards. In PwCOPD, OEP has been used to investigate dynamic

Table 6 Studies of Breathing Mechanics in PwCOPD

Study	Subjects	Conditions	Dependent Variables	Findings
Barros de Sá, et al[179]	28 PwCOPD (14 Tx group; 14 controls)	Single session of rib cage muscles stretching in treatment group	Compartmental volumes using OEP EMG	Tx group increased pulmonary and abdominal rib cage tidal volume Decreased activity in sternocleidomastoid and upper trap
Bhatt, et al[180]	297 PwCOPD (3 groups based on rankings of spirometry compared to CT emphysema)	Inspiratory and expiratory CT images	Jacobian determinant Strain information Anisotropic deformation index	All three dependent variables were associated with FEV_1 Variability of Jacobian and strain may be markers of biomechanical lung heterogeneity
Bianchi, et al[110]	30 PwCOPD	Supervised pursed-lip breathing	Compartmental volumes and displacement using OEP	Two different pursed-lip breathing patterns identified: euvolumics and hyperinflators
Binazzi, et al[181]	15 PwCOPD	Quiet breathing, reading aloud, singing, and high-effort whispering	Chest wall motion using OEP	Phonation imposes breathing more with the abdomen in men Females used more costal breathing compared to men
Bodduluri, et al[182]	490 PwCOPD	Inspiratory and expiratory CT images	St. George Respiratory Questionnaire 6MWD BODE index Wall area percentage Jacobian determinant	Jacobian determinant was associated with the St. George Respiratory Questionnaire, 6MWD, and BODE index
Capeletti, et al[183]	25 PwCOPD	Pre/post adapted Glittre-Activities of Daily Living test	Compartmental volumes using OEP	Reduction in upper thoracic contribution with no change in lower thoracic contribution post test Increase in abdominal compartment contribution post test
Chynkiamis, et al[184]	14 PwCOPD	Intermittent cycle ergometer exercise bouts with portable noninvasive ventilation or pursed-lip breathing during recovery	Compartmental volumes using OEP	Two groups of dynamic hyperinflation responders: 7 subjects responded to portable noninvasive ventilation (responders) and 7 responded to pursed-lip breathing (non-responders) Responders reduced end-expiratory dynamic hyperinflation primarily by reducing abdominal compartment volume
Gagliardi, et al[185]	14 PwCOPD	24-session exercise program	Compartmental volumes using OEP	No change in compartmental volumes
Kruapanich, et al[186]	21 PwCOPD 21 controls	Pre/post unsupported arm elevations (resting, shoulder flexion, scaption, and abduction)	Compartmental volumes using OEP Thoracoabdominal asynchrony	PwCOPD had significantly less volume in the chest wall and rib cage compared to controls Volume of the pulmonary rib cage in PwCOPD was significantly less during the three shoulder elevations compared to controls Thoracoabdominal asynchrony was affected in PwCOPD during scaption and abduction

(*Continued*)

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Table 6 (Continued).

Study	Subjects	Conditions	Dependent Variables	Findings
Lee, et al[187]	30 PwCOPD	Pre/post inspiratory muscle training at 30% and 50% of maximal inspiratory pressure	EMG	Activation of the sternocleidomastoid and diaphragm increased during 30% and 50% training compared to quiet breathing Compared to the diaphragm, the sternocleidomastoid was activated to a greater extent
Mendes, et al[188]	17 PwCOPD	Pre/post quiet, diaphragmatic, and diaphragmatic + pursed-lip breathing	Compartmental volumes using OEP Thoracoabdominal asynchrony	Abdominal contribution was less than 50% for all three breathing conditions During diaphragmatic + pursed-lip breathing, the percent contribution of the pulmonary rib cage increased compared to quiet breathing Thoracoabdominal asynchrony was increased during diaphragmatic and diaphragmatic + pursed-lip breathing compared to quiet breathing
Priori, et al[189]	23 severe PwCOPD 12 controls	Quiet breathing in seated and supine positions	Thoracoabdominal asynchrony using OEP Diaphragm zone of apposition	In both seated and supine, controls had no thoracoabdominal asynchrony PwCOPD was similar to controls during seated During supine, asynchrony between pulmonary rib cage and abdominal compartments emerged in PwCOPD PwCOPD had greater diaphragmatic displacement when seated compared to controls with no difference in supine
Romagnoli, et al[190]	13 PwCOPD	No exercise, incremental and constant load unsupported arm exercise	Compartmental volumes using OEP Thoracoabdominal asynchrony	Chest wall dynamic hyperinflation was not found during constant unsupported arm exercise Thoracoabdominal asynchrony was not associated with dyspnea Arm symptoms stopped exercise, not dyspnea
Willeput, et al[154]	11 PwCOPD	Spontaneous breathing, low-frequency breathing, lower level breathing (prolonging expiration), high level breathing (emphasizing inspiratory effort), abdominodiaphragmatic breathing (inspiration with diaphragm alone and expiration with contraction of abdominal muscles); thoracic breathing (inspiration using thoracic accessory muscles, passive expiration)	Rib cage and abdominal motion	In most subjects, abdominodiaphragmatic breathing induced paradoxical movements compared to spontaneous breathing
Yan, et al[21]	19 PwCOPD	Three full inflations, three maximal sniff maneuvers, and return to spontaneous breathing	Respiratory flow Oesophageal and gastric pressures Motion of rib cage and abdomen Diaphragm electrical activity	PwCOPD divided into passive expiration group (n=9) and active expiration group (n=10) Most variables not different between groups The active group derecruited the diaphragm and recruited inspiratory rib cage muscles compared to the passive group

Abbreviations: Tx, Treatment; OEP, optoelectronic plethysmography; EMG, electromyography.

hyperinflation, dyspnea, chest wall volumes, and the effect of bronchodilators during exercise.[105,109–111] For a more exhaustive review regarding the use of OEP in clinic and research see Massaroni et al.[112]

Mechanomyography is another tool that has been used to assess respiratory muscle activation during breathing. Using a microphone or accelerometer, the oscillations of the muscle surface due to change in muscle shape from contraction can be recorded. This technique has not been widely used in PwCOPD. The few studies that have been done suggest its use for respiratory effort, muscular function such as efficiency, and asynchrony.[113–116] In PwCOPD, muscle activation using mechanomyography has a strong to moderate association with pulmonary function.[117] In PwCOPD and heart failure, mechanomyography has shown potential at validly identifying respiratory muscle activation.[118] Most recently, mechanomyography has been combined with bioimpedance to monitor respiratory activity.[119] Additionally, these sensors may hold vast clinical utility of monitoring pulmonary disease through monitoring of lung sounds and breathing patterns.[120]

Future Directions

With the advancements in technology, it is logical to question whether or not laboratory-based biomechanical evaluations will be needed. Motion analysis in the laboratory is still the gold standard. However, laboratory- or even clinic-based movement does not always reflect everyday movement. Take for example gait speed. Gait speed differs based on the method in which it is recorded.[121] If taken in clinic, it may not accurately reflect gait speed in community settings.[122]

Wearable sensors offer an avenue to capture everyday movement passively. In particular, wearables data are being added to large scale projects such as the COPD Biomarker Qualification Consortium and Mobilise-D. Compared to adults aged 18–49 years, those aged 50 years and older use wearables, smartphones, and smart home technology at the same pace.[123] These technologies contain a wide variety of sensors from inertial measurement units that contain an accelerometer, gyroscope, and magnetometer, bioelectrical impedance, to optical and temperature sensors. Major advancements in materials and mechanics have resulted in the development of soft, "skin-like" devices that closely match the mechanical properties of biological tissue.[124–126] The ability for these electronic devices to bend, twist, and stretch is accomplished by utilizing elastically deformable electrical conductors that provides mechanically robust electrical connectivity between solid-state elements. Current approaches include deterministically patterned metal wiring,[127–130] percolating networks of conductive nanoparticles,[131–133] and conductive fluids such as carbon filled grease,[134] liquid metals,[135–138] and ionic fluids.[139–142] For widespread use and entry into clinical research, these soft wearable sensors must be validated against existing clinical gold-standards and seek US Food and Drug Administration approval.

Monitoring movement and health status using wearables will present clinicians and researchers with a new challenge: big data. It will also create opportunities to provide for "real-time" monitoring of "real-world" functioning. Deciphering what features of collected data is relevant for clinical care. Continuously sending raw data from users to a cloud center raises challenges for communications networks. It inevitably creates computing bottlenecks of health information management at the cloud center. More importantly, sharing user's health information to untrusted cloud server is not acceptable due to privacy concerns. And the sensed health data has numerous features/attributes, which should be carefully extracted for modeling. The computational cost of extracting massive features increases exponentially, so that the problem cannot be easily solved in a reasonable time. To this end, distributed learning can offload computations for relevant data models to the local devices, such as smartphones. Only the relevant information is sent to the cloud center to be aggregated and used to update a universal decision-making model, which in turn saves communication cost and protects the raw data confidentiality. On the other hand, cloud-based systems may increase opportunity for open datasets being prioritized in grant applications. Wearables offer an immense opportunity for open science and data sharing.

COPD is a markedly heterogeneous condition. However, subtyping PwCOPD into meaningful subgroups has been problematic. Studies of biomechanics in PwCOPD, like many other studies, have not focused on the identification of subtypes. This may be a fruitful area for future studies.

Advanced Analytics

In addition to identifying relevant features in sensor data, these individual data streams can provide a wealth of information. Healthy rhythmic biologic processes are marked by variability, complexity, and homeokinesis, which is the ability to maintain an ordered system that fluctuates within an acceptable range.[143–145] The ability to make flexible adaptations to everyday stresses allows a wide range of potential behaviors, leading to systems that are adaptable and flexible in an unpredictable and ever-changing environment.[80] These fluctuations can be quantified by assessing variability, which measures a characteristic of the distribution, and by assessing their complexity, which quantifies their irregularity and thus their independence from other rhythmic processes. Biological rhythms not only fluctuate, they interact with each other. As consequence, they can be coupled. PwCOPD demonstrate abnormal coupling of gait and respiratory rhythms, demonstrating a very rigid coupling across different walking speeds.[146,147]

Clinical Perspectives

It is clear that PwCOPD have functional limitations that can be assessed by biomechanical measures. Development of biomechanical outcomes could provide important novel measures to guide clinical care and facilitate the development of novel treatments. It will be important for clinical care to include assessments of balance and gait during patient intake as these are clinically important outcomes in their own right. Potentially adding a balance confidence or previous falls question will identify individuals that are at high risk for future falls. Further, review of balance and balance recovery training in pulmonary rehabilitation programs may provide an opportunity to improve programming and enhance these skills. Gait speed may be a potentially simple assessment to add to office visit intake. A log of gait speed over multiple office visits will allow healthcare providers to identify a minimal clinically important difference in the decline in speed over time. Recording gait speed over 4 meters has been shown to be responsive to longitudinal change in COPD.[148] In addition, standardizing 6MWT assessments across healthcare providers will ensure that changes in distance are due to the patient and not the methods used for testing.[10]

In the official ATS/ETS statement on pulmonary rehabilitation,[149] balance assessment is encouraged yet no information is provided on what kind of assessment or how often this should be done. A recent review of balance assessments in COPD[38] offers guidance with regard to falls and fall history screening; however, this is without a clear delineation of which tool would be best as there are multiple factors that go into proper selection of an assessment tool. Balance training during pulmonary rehabilitation has been shown to be effective in improving balance, yet unclear regarding the long-term effect on falls.[150] As balance assessment and training in PwCOPD are still relatively new concepts, further development of interventions is required. As of 2021, balance assessment and training were not listed as essential components of pulmonary rehabilitation by the ATS,[151] indicating work still needs to be done in establishing them as critical components. Biomechanical assessments would strongly assist in guiding best practices of which assessment tools and/or interventions are most effective.

There is further evidence that non-specific pulmonary rehabilitation has been effective in improving gait speed[152] and biomechanical gait outcomes[67] in a subset of PwCOPD. Updated pulmonary rehabilitation programs are encouraged to include gait assessment and training[153] suggesting that gait training could have a clinical impact on 6MWD, balance, and fall risk. Biomechanical assessment of gait may be useful to identify PwCOPD that have an altered gait pattern providing those that need it most with additional/specific training sessions during pulmonary rehabilitation. Further, there is a lack of knowledge regarding whether or not gait improvements made during pulmonary rehabilitation have translated to daily life.

Breathing exercises have played an important role in treatment of PwCOPD. Monitoring thoracoabdominal motion during breathing therapy is important as abdominodiaphragmatic breathing ("inspiration with the diaphragm 'alone' and expiration with a contraction of the abdominal muscles") may induce the most dyssynchronous thoracoabdominal motion;[154] whereas, diaphragmatic breathing ("belly breathing") is associated with more effective breathing outcomes.[155–157] During the 6MWT, rib cage excursion was an independent predictor of total 6MWT distance.[100] Therefore, understanding the extent of dyssynchronous thoracoabdominal motion in a patient will have an impact on treatment. Important too will be biomechanical analyses to evaluate the effectiveness of newer interventions to improve breathing mechanics, and potentially balance and gait, such as singing for lung health,[158–160] dancing,[161,162] yoga,[163,164] liuzijue qigong,[165,166] and tai chi.[167–169]

Muscle mechanics may have an impact on clinical care; however, this is yet to be fully determined. Additional research is needed to understand the effects of COPD on muscle tissue tension, extensibility, elasticity, and irritability. Based on current pulmonary rehabilitation recommendations, a comprehensive assessment should include inspiratory and peripheral muscle strength and endurance assessments.[151] Further, pulmonary rehabilitation programs should include resistance and strength training as the benefits have been well documented.[149]

Advancements in wearable technology will likely have a significant impact on clinical care. For example, sensors attached to the arm used to record upper extremity function (ie, rapid elbow flexion) in PwCOPD hospitalized for an exacerbation may be useful for prediction of 30-day readmission.[170] Another potential target for wearables is in identifying disease severity during everyday activities such as walking.[171] In addition to prognostic value, the ability to capture real-time data in real-world settings opens up entirely novel opportunities for patient monitoring. For example, objective patient monitoring could provide more accurate information regarding falls and physical activity. Recall of falls is subject to memory and recall of physical activity is subject to bias, stigma, and/or embarrassment. This can provide novel outcomes to facilitate the development of new treatments and to create measures to gauge the impact of treatments in the "at home" setting.

Conclusion

In conclusion, biomechanical assessments are complementary to physiological assessments. Biomechanical measures offer an additional dimension of assessment compared to physiological laboratory measures, as biomechanics can capture what patients are actually doing as well as their capability. Consideration of function and movement in clinical care will lead to more comprehensive treatments or referrals to therapists (eg, physical therapy). Ensuring that PwCOPD are capable of more than just movements for instrumental activities of daily living, will make a direct impact on their quality of life. Having the confidence to move about in their communities or play with their grandchildren is important in maintaining social connections and overall happiness.

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Disclosure

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