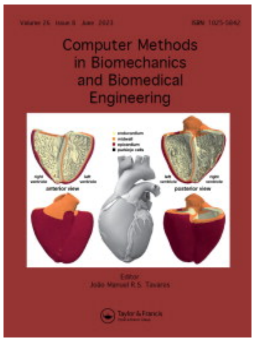

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Intrinsic factors contributing to elevated intra-abdominal pressure

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ABSTRACT
Pelvic floor disorders affect 24% of US women, and elevated intra-abdominal pressure may cause pelvic injury through musculoskeletal strain. Activity restrictions meant to reduce pelvic strain after traumatic events, such as childbirth, have shown little benefit to patients. Reported high variability in abdominal pressure suggests that technique plays a substantial role in pressure generation. Understanding these techniques could inform evidence-based recommendations for protective pelvic care. We hypothesized use of a motion-capture methodology could identify four major contributors to elevated pressure: gravity, acceleration, abdominal muscle contraction, and respiration. Twelve women completed nineteen activities while instrumented for whole body motion capture, abdominal pressure, hip acceleration, and respiration volume. Correlation and partial least squares regression were utilized to determine primary technique factors that increase abdominal pressure. The partial least squares model identified two principal components that explained 59.63% of relative intra-abdominal pressure variability. The first component was primarily loaded by hip acceleration and relative respiration volume, and the second component was primarily loaded by flexion moments of the abdomen and thorax. While reducing abdominal muscle use has been a primary strategy in protective pelvic floor care, the influence of hip acceleration and breathing patterns should be considered with similar importance in future work.

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Pelvic Floor Disorders; Motion Capture; Intra-abdominal Pressure

1. Introduction

Pelvic floor disorders (PFDs) often result from damage or weakening of the musculoskeletal tissues that line the bottom of the abdominal cavity. PFDs will affect 1 in every 4 women during their lifetime (Nygaard 2008). A woman's lifetime risk of surgical intervention for PFDs is 10%, and 30% of women receiving surgery will undergo 2 or more procedures (Nygaard 2008; DeLancey 2005). The pelvic floor is responsible for supporting pelvic organs, such as the bladder, uterus, and rectum, and plays a key role in proper function of these organs. When the pelvic floor cannot provide adequate support, symptoms of urinary incontinence, fecal incontinence, and pelvic organ prolapse develop. The weight of pelvic organs produces strain on the pelvic floor, and this strain can increase during dynamic activities and is often measured as intra-abdominal pressure (IAP). While the exact role of IAP on PFDs is still uncertain, there is a predominant hypothesis that high IAP overloads the pelvic floor, and over time can damage the musculoskeletal tissues (Bø and Nygaard 2020).

Age, parity, and obesity are known to increase the risk of a PFD (Nygaard 2008), but the prevalence of the disease among young, healthy, and nulliparous women indicates that there remain unidentified pathophysiologic mechanisms. IAP became suspect due to the increased prevalence of PFDs among young athletes participating in high-impact and high-exertion sports (Bø and Nygaard 2020; K 2004). The idea of IAP overloading the pelvic floor has also guided postoperative activity restrictions, such as restrictions from lifting objects more than 4.5 kg, aimed to protect healing pelvic tissues. Postoperative activity restrictions have shown little effect on surgical outcomes, leading many clinicians to question whether postoperative restrictions make sense (Mueller et al. 2017). Many restricted activities do not raise IAP more than unavoidable activities, such as getting out of a chair, but how these restricted activities are executed can affect the IAP produced (Weir et al. 2006; Guttormson et al. 2008; Yamasato et al. 2014).

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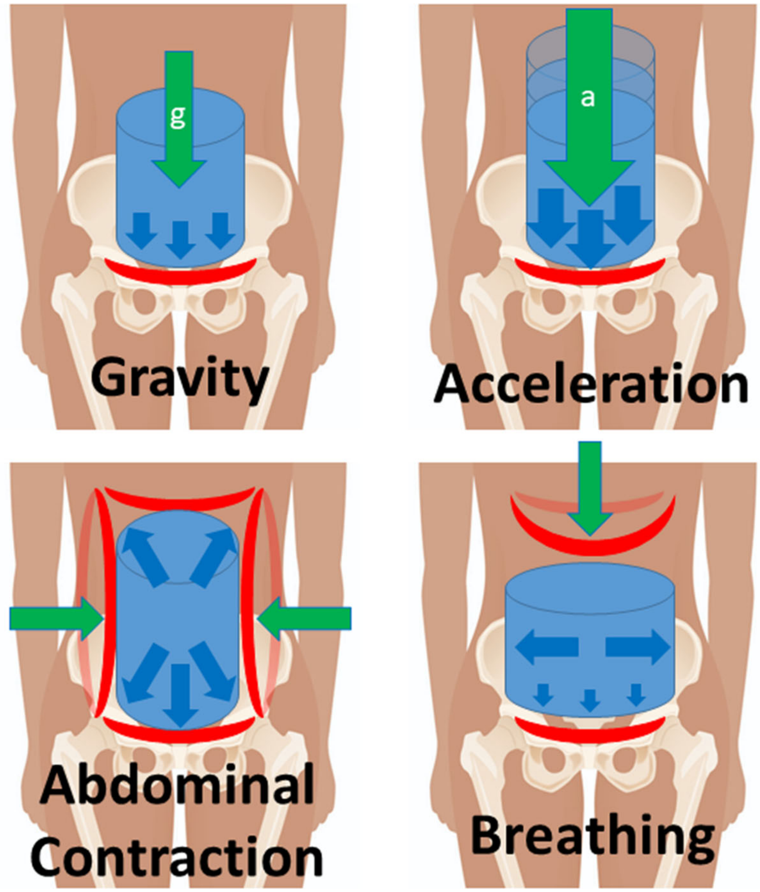

Figure 1. Four-element model for IAP generation. Green arrows indicate the primary action that leads to increased IAP. Blue cylinders are the abdominal compartment. Blue arrows are the resulting intra-abdominal pressure forces. Red lines are the pelvic, abdominal, and diaphragm muscles that enclose the abdominal cavity.

A significant knowledge gap exists about technique-based differences in IAP generation. Understanding this relationship could promote evidence-based technique recommendations, reducing activity restrictions for women recovering from surgery and allowing them to return to an active lifestyle.

Many studies have found high intra- and inter-subject IAP variability when performing a single activity (Coleman et al. 2015; Cresswell and Thorstensson 1994; Egger et al. 2015; Hackett and Chow 2013; Hagins et al. 2004; Hagins et al. 2006; Hitchcock et al. 2020; Hsu et al. 2018; Kawabata et al. 2010; Essendrop and Schibye 2004; Sapsford and Hodges 2001; Junginger et al. 2010). These studies have looked at how IAP varies during lifting with varying breathing techniques (Hagins et al. 2004; Hagins et al. 2006), lifting while wearing an abdominal belt (McGill et al. 1990; Cholewicki et al. 1999), various walking speeds and carrying techniques (Coleman et al. 2015), voluntary abdominal muscle contraction (Sapsford and Hodges 2001; Junginger et al. 2010), and hip acceleration (de Gennaro et al. 2019). These studies often suffer from a lack of ecological validity and have attempted to control for factors beyond the study scope that may confound IAP results, often by restricting a participant's plane of movement or providing explicit instructions how to complete a task. While these results can provide recommendations for IAP reduction in specific cases, the results may not accurately represent more complex movements that occur during real-world activities. A more holistic understanding of how IAP is generated could lead to evidence-based IAP reduction strategies aimed at protecting the pelvic floor.

Based on the existing literature and our experience measuring IAP, we hypothesized there are four major contributors to generating IAP: gravity, acceleration, abdominal muscle contraction, and breathing (represented in Figure 1). The gravitational pull of the abdominal organs is resisted by the pelvic floor, inducing a static resting pressure while upright. IAP generated by acceleration has an additional momentum component of the abdominal viscera that can significantly increase the total energy and force applied to the pelvic floor. Abdominal muscle contraction generates an inward circumferential force that is resisted by the pelvic floor and diaphragm, resulting in elevated IAP. Breathing alters the volume and shape characteristics of the abdominal cavity and surrounding tissues, modifying how gravity, acceleration, and muscle contraction effect IAP when measured at the pelvic floor.

We hypothesized that these four major contributors to IAP generation could be identified using a motion capture approach combined with continuous IAP recording. 3 D motion capture provides quantifiable and detailed data on body movements to model biomechanics during complex movements. To measure IAP, we utilized our previously reported ambulatory intra-vaginal transducer, which has been shown to provide more accurate IAP measurements during rapid pressure changes, and has been used in numerous human trials to measure IAP during physical activity (Coleman et al. 2012; Hsu et al. 2012). Coupling existing motion capture techniques with our ambulatory IAP measurement technology (Niederauer et al. 2017), we hypothesized that elevated IAP would be associated with each of the four major contributors to generating IAP.

2. Methods

All Study materials were approved by the University of Utah IRB (IRB_00115498) before recruiting women in the greater Salt Lake City area. Women were required to be between the ages of 18 and 54 and able to insert a tampon. Women were excluded if they: (i) experienced bulging beyond the vagina, (ii) had a history of pelvic surgery other than hysterectomy, (iii) currently used a vaginal contraceptive or pessary, (iv) experienced unusual vaginal bleeding or discharge, (v) had a musculoskeletal injury in the last three months, (vi) were pregnant or delivered a baby within the last year, or (vii) had any risk factors related to exercise (PAR-Q (Shephard 1988)). No previous data were available on which to base the statistical design of the study, therefore 12 women were recruited to ensure adequate precision in the means and variances captured in the study while balancing study feasibility and regulatory considerations (Julious 2005).

An intra-vaginal transducer (IVT) was used to collect intra-abdominal pressure data (Niederauer et al. 2017). The IVT connects with an instrumentation module (IM) that collects and stores data on an onboard microSD card. The IM is affixed to the hip when in use and includes an inertial module unit (STMicroelectronics, LSM330DLC) to measure triaxial acceleration at the hip (Niederauer et al. 2022). Two piezo-electric respiration transducers (UFI, Model 1132) were wired to the IM to measure respiration volume via cross-sectional area changes of the thorax and abdomen, respectively. The IM sampled IAP, acceleration, and respiration data at 200 Hz to match the data collection rate of the motion capture system.

Based on motion-capture lab availability, either a 10 or 12-camera Vicon motion capture system (Vicon Motion Systems, Centennial, CO, USA) was used to collect 3 D motion data from participants at a rate of 200 Hz. Two AMTI MSA-6 biomechanics platforms, used in the 10-camera lab, or two AMTI OR6-7 biomechanics platforms, used in the 12-camera lab, (Advanced Medical Technology, Watertown, MA) recorded ground reaction forces at 1000 Hz and were used in conjunction with trajectory data to calculate inverse dynamics to determine joint moments at 200 Hz. Retroreflective markers (14 mm diameter, Vicon Motion Systems, Centennial, CO, USA) were placed on bony prominences of study participants utilizing a modified gait analysis marker set (Nexus plug-in gait marker set; Vicon Motion Systems, Centennial, CO) to track 16 segments (2 feet, 2 shanks, 2 thighs, pelvis, abdomen, thorax, head, 2 arms, 2 forearms, 2 hands).

Participants began the study protocol in the recommended static calibration pose (Vicon Nexus 2.0, Vicon Motion Systems, Centennial, CO). Participants then performed three consecutive Valsalva maneuvers while seated. Participants were instructed to 'breath in as deeply as possible, then try to exhale as forcefully as possible while holding your breath'. The inspiration volume measured immediately before Valsalva and the IAP generated during Valsalva were used to normalize data to individuals, described later. Participants completed three repetitions of 19 tasks throughout the study. At the beginning of each tasks, participants simultaneously coughed and stepped on one of the ground reaction force (GRF) plates. The cough and step produced sharp peaks in IAP and GRF data that were used to synchronize data from the motion capture system and IM.

Participants performed two *sit-to-stand* tasks beginning seated on a 45 cm high box. The first began with the participants' feet positioned so their knees were at approximately *90 degrees flexion*, the second with their knees at approximately *100 degrees flexion* (Stevermer and Gillette 2016). For each sit-to-stand task, participants stood and returned to their original seated position three times in succession and were given no instruction on how to perform the task other than to not place their hands on the box. Following the sit to stand task, a v-grip handlebar was bolted to the edge of a GRF plate so the participant could perform a *Jackson leg lift test*, an isometric lifting test (Jackson 1999). Participants performed three lifts at *50% effort* and three lifts at *100% effort* of their perceived maximum lifting effort. Participants completed 5 walking tasks: *unloaded, asymmetrically loaded, symmetrically loaded, front waist carry, and front chest carry* (Rose et al. 2013). For each walking task, participants were instructed to walk the length of the motion analysis lab three times, making contact with the force plates at the center of the room each time, but no specific instructions were given on how to contact the plates. In the unloaded case, participants completed the walking task without any weights. For asymmetric loading, participants carried a 5 kg dumbbell immediately lateral their pelvis in their dominant hand. The symmetric loading task was performed with two 2.5 kg dumbbells, one in each hand carried to the side of the pelvis. The front waist carry task had participants hold a 5 kg dumbbell immediately anterior their pelvis, and was held with both hands. The front chest carry had participants hold a 5 kg dumbbell with both hands at approximately 30 cm directly anterior their mid-sternum.

Participants completed four lifting tasks, lifting a 60 cm x 30 cm x 15 cm box weighing approximately 0.5 kg from the ground to a 120 cm tall table placed 60 cm directly in front of the participants feet. The lifting trials varied the weight placed in the box, either 5 kg or 10 kg, and the positioning of the box on the ground, either directly in front of the participant or located 60 degrees to the dominant side of the participant (Granata et al. 1999). As with other tasks, the lifting task was performed with three successive repetitions for each weight and position combination (*lifting 5 kg front, 10 kg front, 5 kg side, and 10 kg side*). Participants performed three repetitions of a *15 cm box drop* and three repetitions of a *30 cm box drop* (Iida et al. 2011). Participants were instructed to stand on the box, move one leg in front of the box, drop off the box without jumping upwards, and perform a two-footed landing on the GRF plates.

Participants completed a *fall recovery* task by standing with their feet together on a GRF plate (Singer et al. 2015). Participants then leaned backward while standing straight with their hands at their side while being supported by a research team member. While participants were leaning at an approximately 20-degree angle and supported, they were given either an audible countdown to release, for the *known release*, or a cue that they would be released at an unspecified time within the next 5 seconds, for the *unknown release*. The research team member then released the participant, who was instructed to take a step or multiple steps to prevent themselves from falling backwards. For the *ball catch* task, a 12 kg medicine ball 30 cm in diameter was suspended with rope at the mid-sternum height for each participant (Kanekar and Aruin 2015). The ball was retracted 2 meters from the participant and held by research personnel. The same countdown strategy used in the fall recovery task was also applied to the ball catch task. Participants were instructed to start with their arms at their sides and to then catch the ball after release with both hands in front of them.

Physiologic data collected by the IM was imported into MATLAB (Mathworks, 2020 b, Natick, MA) with a custom parsing script. Hip acceleration magnitude was calculated using triaxial accelerometer measurements from the IM. Relative respiration, reported as a percentage of an individual's maximum, was calculated by summing the abdominal and thoracic respirometer measurements, then dividing by the single maximum inspiration volume recorded during the Valsalva task, where participants were instructed to 'breath as deeply as possible'.

Marker trajectories and ground reaction forces were recorded, synchronized, and initially post processed to fill any gaps in trajectories using Vicon Nexus (Vicon Nexus, V 2.0, Centennial, CO). Next, the data was imported into Visual3D (C-Motion, Germantown, USA) to calculate biomechanical joint data in three dimensions for the ankles, knees, hips, abdomen, and thorax joints. A low pass, zero-phase shift Butterworth filter at 6 Hz and 20 Hz was used to filter marker trajectory and kinetic data, respectively, based on visual inspection and residual analysis (Winter 2005). Biomechanical joint data was imported to MATLAB and synchronized with IM data using a custom MATLAB graphical interface to align the cough and step data peaks at the beginning of each task. Figure 2 shows representative synchronized data from a 30 cm box drop task. In this box-drop example, elevated IAP was mainly associated with hip acceleration at the moment of ground contact.

The maximum IAP generated by each participant during every task was calculated using a mean maximum approach, which produces more reliable measures of maximum IAP (Hamad et al. 2013). Mean maximum was calculated with the three maximal IAP points separated by at least 1 second. The three maximal points used for mean maximum calculation were

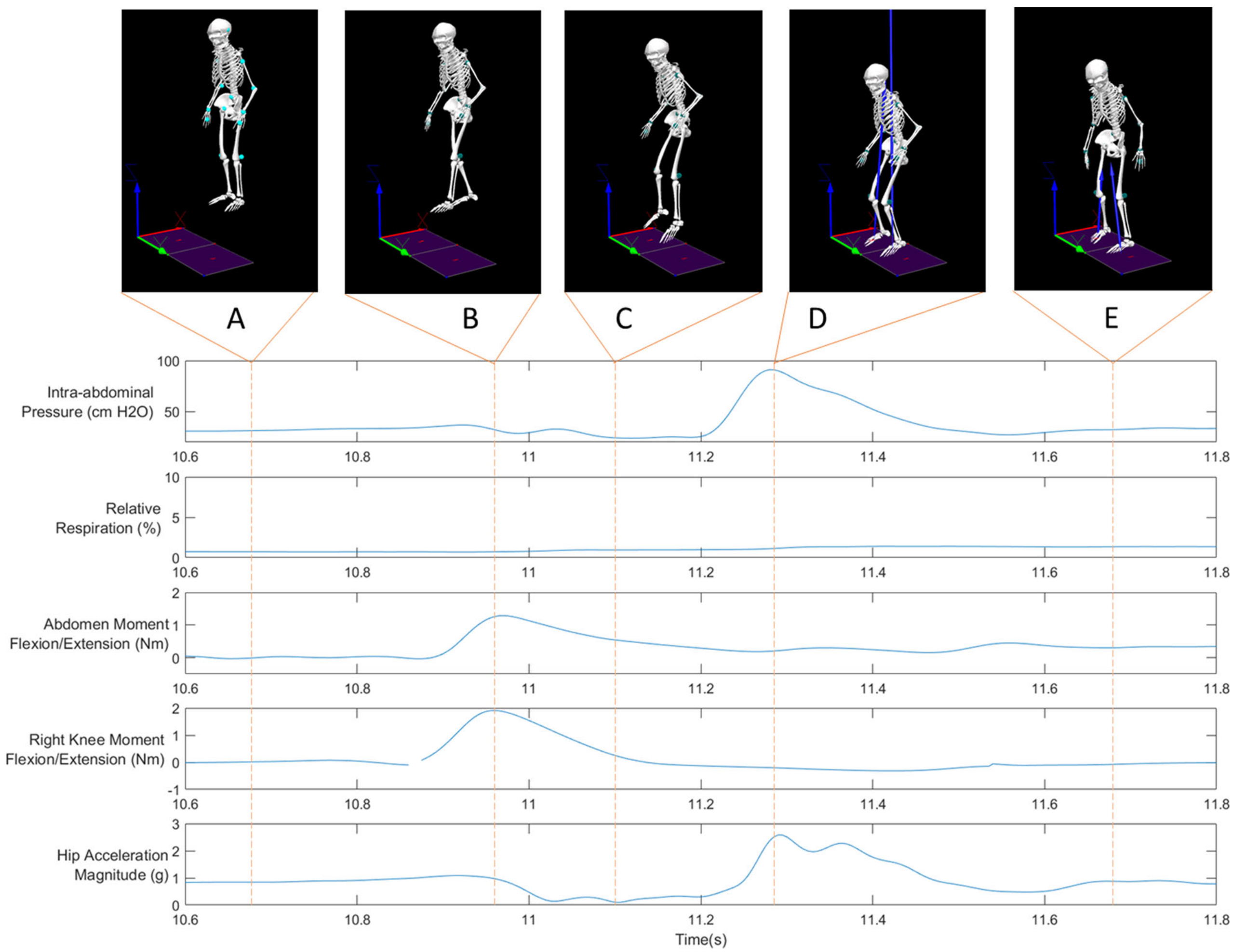

Figure 2. Representative Synchronized Data from 30 cm Box Drop. (Above) Images showing the model of the participant at five discrete time points during a single box drop. (Below) Synchronized physiologic and biomechanical joint data with vertical dashed lines indicating discrete time points associated with the images above. (A) Participant is standing stationary on the 30 cm tall box. (B) Participant removes one foot from the box and holds it approximately 30 cm in front of the box, increasing knee and abdomen flexion moments, but no notable increase in IAP. (C) Participant has removed second foot from box and is in free-fall, there is a reduction in hip acceleration and IAP while falling. (D) Participant makes contact with the ground, creating a sharp increase in both hip acceleration and IAP, but no notable increases in abdomen or knee moments. (E) Participant remains standing after completing box drop and all physiologic and biomechanical joint data return to baseline values.

also utilized in a repeated measure analysis of variance (RANOVA) to examine the effects of participants' characteristics as well as the intra-participant variability of IAP generation.

Data included in subsequent analysis spanned from 0.5 seconds after the cough-step synchronization to one second after completing the third repetition of a given task. IAP data were normalized to each participant utilizing the maximum IAP generated during the volitional Valsalva maneuver. Previous studies have suggested relative IAP to be more relevant from a functional capacity perspective than absolute IAP (Essendrop and Schibye 2004; Dietze-Hermosa et al. 2020), much like oxygen consumption is measured as a percentage of an individual's maximum where individuals have differing maximum oxygen consumption capacities. The single maximum IAP generated during the seated Valsalva was considered 100% relative IAP, and any higher IAP was reported above 100%.

In order to examine the primary factors of IAP generation for different tasks, data for each task were pooled from all participants. Pearson's correlations were calculated between IAP and each biomechanical joint or physiologic data variable using the task-pooled data. The top three absolute correlates are presented for each task. Given the high dimensionality and likelihood of multicollinearity of our data, we utilized a partial least squares regression (PLSR) to model generation of IAP. Predictor variables used for correlation and PLSR modeling were normalized using a median and median absolute deviation (MAD) approach. We elected to use a median and

Table 1. Mean Maximum IAP Results. The mean and standard deviation of the three maximal IAP peaks for each task and participant. Peaks used for analysis were separated by at least 1 second. Shaded areas indicate the highest mean maximum IAP for each participant. The right-most column shows the single maximum Valsalva IAP used for normalization in subsequent analysis. The bottom row shows the mean maximum IAP pooled across all participants for each task.

Participant Mean Maximum IAP (cm H20) Mean (SD)	Valsalva	Sit to Stand 90	Sit to Stand 100	Jackson Leg 50%	Jackson Leg 100%	Walk Unloaded	Walk Asymmetric Loaded	Walk Symmetric Loaded	Walk Waist Carry	Walk Chest Carry	Lift 5kg Front	Lift 10kg Front	Lift 5kg Side	Lift 10kg Side	Box-Drop 15 cm	Box-Drop 30 cm	Fall Recovery Known Release	Fall Recovery Unknown Release	Ball Catch Known Release	Ball Catch Unknown Release	Single Maximum Valsalva IAP
Participant 1	136.8 (7.2)	53.4 (8.3)	55.6 (7.5)	71.4 (3.0)	**142.7 (2.7)**	51.4 (0.8)	52.7 (1.3)	51.6 (0.4)	52.6 (4.1)	54.0 (2.1)	68.9 (1.7)	75.3 (5.5)	69.6 (3.1)	83.3 (3.0)	67.8 (1.9)	65.0 (15.0)	84.6 (4.2)	115.2 (12.3)	43.3 (0.7)	46.6 (3.2)	144.4
Participant 2	99.9 (16.9)	41.0 (3.2)	40.6 (3.0)	33.9 (3.4)	59.2 (14.4)	44.8 (1.7)	45.8 (1.1)	45.7 (0.8)	46.1 (1.1)	63.0 (21.3)	49.4 (4.3)	61.8 (2.1)	58.6 (4.6)	75.4 (4.6)	96.1 (4.5)	**113.8 (4.5)**	86.2 (10.2)	84.8 (6.3)	39.4 (4.4)	38.3 (1.3)	118.8
Participant 3	76.5 (1.7)	72.2 (5.0)	45.0 (3.2)	57.1 (2.5)	88.7 (2.4)	43.0 (0.6)	47.8 (0.3)	45.4 (1.0)	48.7 (1.0)	52.5 (1.3)	72.0 (3.1)	87.5 (3.4)	67.2 (2.9)	81.4 (7.1)	75.7 (5.0)	**90.3 (1.4)**	77.3 (2.3)	67.1 (1.9)	39.3 (1.1)	37.0 (2.2)	77.9
Participant 4	68.6 (9.3)	39.1 (5.4)	43.8 (3.2)	25.6 (2.5)	44.0 (3.3)	30.7 (1.7)	29.2 (0.5)	30.3 (0.3)	36.0 (1.0)	53.6 (3.6)	42.0 (9.1)	72.4 (7.6)	37.0 (1.5)	75.6 (4.6)	79.1 (11.8)	**83.9 (6.3)**	52.2 (5.4)	62.5 (3.7)	38.7 (10.1)	28.9 (1.5)	77.9
Participant 5	**104.4 (5.5)**	65.2 (2.1)	43.8 (1.8)	35.2 (1.4)	35.2 (1.4)	44.4 (0.8)	45.8 (2.0)	46.9 (3.0)	44.6 (0.2)	45.7 (1.7)	56.9 (2.5)	71.5 (9.6)	88.5 (1.8)	77.1 (14.0)	79.2 (1.1)	92.2 (4.0)	80.5 (9.6)	83.8 (5.2)	41.2 (2.9)	37.9 (1.7)	110.7
Participant 6	**187.4 (12.2)**	153.7 (10.8)	106.2 (17.2)	64.0 (4.5)	59.7 (3.5)	65.7 (3.0)	66.4 (1.3)	66.7 (2.4)	66.5 (1.0)	67.9 (2.5)	69.7 (11.9)	54.7 (4.0)	53.9 (5.7)	48.0 (4.7)	36.2 (1.0)	45.6 (6.1)	87.3 (4.6)	71.2 (13.2)	36.3 (2.1)	33.4 (0.7)	197.5
Participant 7	**178.7 (25.0)**	36.8 (2.5)	42.4 (17.4)	24.5 (4.8)	144.1 (21.3)	39.7 (1.1)	41.2 (1.2)	41.8 (1.8)	43.7 (0.8)	50.3 (2.7)	19.7 (1.4)	19.5 (1.3)	23.6 (3.1)	69.9 (19.8)	46.6 (17.1)	88.4 (10.1)	84.1 (1.4)	68.1 (22.5)	24.0 (1.6)	24.6 (1.1)	196.4
Participant 8	62.4 (4.5)	60.0 (2.7)	61.0 (5.8)	59.0 (2.1)	89.5 (7.8)	66.1 (1.9)	64.4 (0.8)	65.0 (0.7)	64.4 (1.6)	69.2 (1.7)	63.7 (5.0)	97.6 (8.1)	76.4 (3.3)	108.2 (8.1)	104.0 (15.8)	135.4 (23.0)	124.5 (15.7)	**136.0 (14.9)**	59.2 (1.4)	55.2 (0.4)	67.4
Participant 9	87.1 (2.5)	41.1 (1.7)	38.4 (2.2)	48.6 (2.4)	**99.4 (8.6)**	43.6 (0.8)	47.6 (0.6)	42.9 (0.9)	44.1 (1.2)	44.3 (0.3)	51.6 (1.1)	68.5 (4.3)	75.2 (6.0)	81.7 (0.5)	82.3 (3.9)	83.6 (2.7)	69.3 (4.0)	70.0 (3.6)	36.7 (1.6)	32.2 (0.6)	89.9
Participant 10	85.1 (15.6)	44.6 (3.2)	46.5 (2.6)	36.3 (1.2)	76.2 (10.8)	49.8 (2.0)	53.3 (1.1)	50.8 (0.7)	51.3 (1.2)	51.4 (1.4)	56.5 (3.2)	84.5 (4.3)	51.3 (0.9)	82.2 (3.2)	76.0 (3.7)	103.1 (4.2)	**111.3 (4.8)**	83.0 (24.9)	40.9 (1.6)	46.4 (3.5)	102.3
Participant 11	68.1 (3.2)	37.1 (3.0)	36.1 (3.1)	29.4 (3.2)	77.0 (6.3)	37.5 (1.1)	38.1 (0.7)	37.2 (1.2)	42.4 (1.1)	44.2 (1.6)	39.7 (2.4)	62.8 (2.1)	56.2 (3.0)	74.1 (1.5)	61.5 (3.5)	**79.8 (0.7)**	65.0 (2.2)	68.0 (0.9)	30.9 (2.0)	29.3 (0.4)	71.7
Participant 12	86.0 (1.0)	53.5 (1.4)	54.7 (4.6)	53.1 (1.4)	72.2 (2.6)	45.0 (0.4)	46.3 (0.4)	45.3 (0.6)	49.0 (2.2)	50.3 (0.5)	62.9 (2.7)	51.6 (5.9)	52.7 (2.5)	87.7 (4.3)	79.7 (5.6)	**110.7 (5.0)**	66.2 (8.0)	63.5 (7.7)	69.1 (7.1)	68.2 (8.1)	87.2
Task Mean Max	94.8	58.1	51.2	44.8	82.3	46.8	48.2	47.5	49.1	53.9	54.4	67.3	59.2	78.7	73.7	91.0	82.4	81.1	41.6	39.8	

MAD normalization approach as some variables were not normally distributed and certain tasks generated extreme values that we did not consider invalid, but would unevenly leverage linear models with mean and standard deviation normalization. Normalization also removed the chance of artificial weighting in the PLSR model due to different measurement units between data variables. The PLSR model was calculated using normalized data with relative IAP as the response variable and all remaining data as predictors. Five principal components were assembled for the PLSR model using a 5-fold cross-validation procedure.

3. Results

Motion capture data were lost in one participant during the ball catch task (both known and unknown release) and in two participants during the front waist and front chest walking trials. Data loss occurred due to visual obstruction of key retroreflective markers around the abdomen, and these data were excluded from analysis in correlation and PLSR modeling. The intra-abdominal pressure data from these tasks were intact and used for mean max (see Table 1) and repeated measures analysis of variance (RANOVA) analysis. Twelve women completed the study protocol. The women were 19 to 37 years of age (mean (SD) 25.6 (±5.6) years), 157 to 178 cm in height (166.6 (±7.0) cm), weighed between 49 and 77 kg (62.9 (±8.7) kg), had BMI values between 19.7 and 24.3 (22.6 (±2.3) km/m^2), and 4 had delivered at least one child vaginally.

The RANOVA results showed no statistically significant effects of participant characteristics: Age ($P = 0.995$), Height ($P = 0.322$), Weight ($P = 0.313$), BMI ($P = 0.315$), and Parity ($P = 0.690$). RANOVA results also showed that the task being performed ($P = 0.259$) and intra-subject variability ($P = 0.315$) were also insignificant, while the participant performing the task ($P = 0.070$) was trending significant.

Figure 3 shows relative IAP data collected during the study from each task. There are 3 distinct task profiles that emerge when examining relative IAP range: low variability, high variability, and low variability with numerous outliers. Low variability tasks, such as walking and ball catch, generate lower levels of relative IAP with a small inter-quartile range. High variability tasks, such as lifting and Jackson leg strength, generate much higher ranges of relative IAP for significant durations, shown by larger inter-quartile range. The low variability tasks with numerous outliers, such as box-drop and

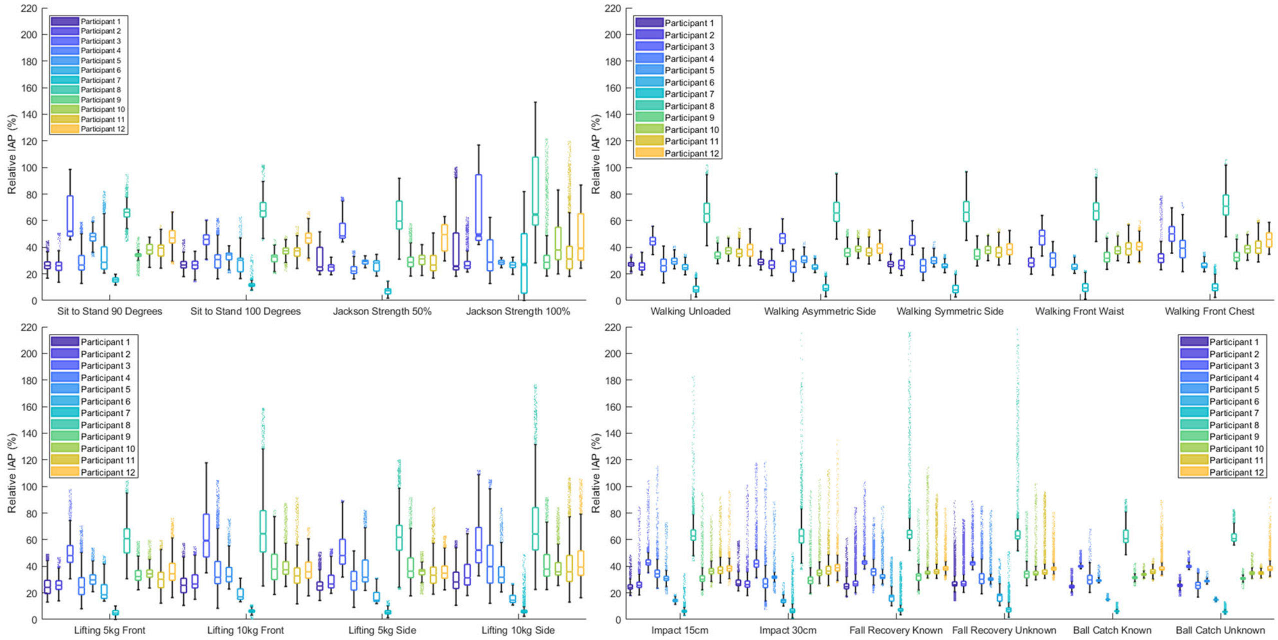

Figure 3. Relative IAP across all participants and all tasks. Each box denotes the inter-quartile range (Q1 to Q3), the black whiskers extending each box denotes the 1.5*IQ range, and individual points beyond the end of the whiskers denote outliers.

fall recovery, generate levels of IAP similar to the high variability tasks, but do so for significantly shorter periods of time, indicated by the small inter-quartile range.

Table 2 shows the three highest correlates to relative IAP for each task in the study. Hip acceleration and relative respiration are the highest correlates in 15 of the 19 tasks. Some tasks have a single primary correlate, such as the box-drop's correlation with hip acceleration, indicating IAP is likely generated in a single unique way for the given task. Other tasks report multiple correlates, such as the 100% Jackson strength test, where IAP generation is likely a function of several factors that may or may not be associated with one another.

Figure 4 shows results of the partial least squares regression (PLSR) performed on data collected from all participants across all tasks. Figure 4A shows the mean relative IAP plotted against the first two principal component (PC) scores. PC scores are the linear combinations of the predictor variables weighted by PC loadings for the given time point. Figure 4B shows the physiologic variable loadings in the first two principal components. The first principal component explained 37.48% of the variability in relative IAP, and was primarily loaded by relative respiration and hip acceleration magnitude. The second principal component explained 22.15% of relative IAP variability, and was primarily loaded by the anterior flexion moments of the thorax and abdomen. The remaining three principal components explained 4.95%, 3.24%, and 1.17% of the remaining relative IAP variability. While other variables do load the principal components, such as knee and hip moments, they do so at diminished levels and may only be associated with relative IAP due to collinearity with the dominant predictors, such as abdomen moments. The surface plot shows higher relative IAP is generated when the first and second principal components are positive. While the second principal component does modify the relative IAP predicted by the PLSR model, these data suggests that respiration volume and acceleration contribute more to elevated IAP across the tasks performed in this study. Figure 4C shows the relative IAP residuals of the PLSR model, which increase linearly with increasing relative IAP.

4. Discussion

To our knowledge, this is the first study to utilize 3-dimensional motion capture with IAP and physiologic measurements across a variety of tasks. Our approach took advantage of participants' full freedom of movement with minimal instructions on how to complete each task, and allowed us to capture and quantify as much variability as possible in different techniques within our study population. We believe this study provides the most generalizable findings of how IAP is generated. Understanding how IAP is generated will provide greater insights into the pathophysiology of PFDs.

While the unrestricted movement and high dimensionality of predictor data are strengths of the study,

Table 2. Top Correlates with relative IAP organized by Task. Data from all participants were pooled by task and the three highest absolute (negative or positive) correlates are presented. Bolded values denote correlations considered moderate ($R > 0.3$).

	Highest Correlation		2nd Highest Correlation		3rd Highest Correlation	
Activity	Kinematic/Physiologic Variable	Pearson's Correlation	Kinematic/Physiologic Variable	Pearson's Correlation	Kinematic/Physiologic Variable	Pearson's Correlation
Sit to Stand 90 degrees	Hip Acceleration	0.135	Relative Respiration	0.128	Abdomen Moment X	0.117
Sit to Stand 100 degrees	Hip Acceleration	0.162	Abdomen Moment X	0.107	Thorax Moment X	0.103
Jackson Strength 50%	Abdomen Moment X	−0.142	Thorax Moment X	−0.116	Relative Respiration	0.099
Jackson Strength 100%	**Relative Respiration**	**0.428**	**Abdomen Moment X**	**-0.303**	Thorax Moment X	−0.257
Walk Unloaded	Hip Acceleration	0.212	Relative Respiration	0.028	L Knee Moment X	−0.019
Walk Asymmetric Side Load	Hip Acceleration	0.207	R Knee Moment X	−0.031	R Hip Moment Z	0.026
Walk Symmetric side Load	Hip Acceleration	0.223	Abdomen Moment X	0.053	Thorax Moment Y	0.045
Walk Front Waist Load	Hip Acceleration	0.240	Thorax Moment X	0.052	Abdomen Moment X	0.039
Walk Front Chest Load	Hip Acceleration	0.227	Relative Respiration	0.043	Abdomen Moment X	0.045
Lifting 5 kg front	Abdomen Moment X	−0.180	Relative Respiration	0.141	L Ankle Moment Z	−0.121
Lifting 10 kg front	Relative Respiration	0.207	Abdomen Moment X	−0.182	R Knee Moment X	−0.156
Lifting 5 kg side	Abdomen Moment X	−0.189	Relative Respiration	0.172	Thorax Moment X	−0.125
Lifting 10 kg side	Relative Respiration	0.265	Thorax Moment X	−0.239	Abdomen Moment X	−0.219
15 cm Box-Drop	**Hip Acceleration**	**0.316**	Relative Respiration	0.073	R Ankle Moment X	−0.069
30 cm Box-Drop	**Hip Acceleration**	**0.402**	R Knee Moment X	0.221	L Knee Moment X	0.198
Fall Known Release	Hip Acceleration	0.182	R Knee Moment X	0.131	Relative Respiration	0.124
Fall Unknown Release	Hip Acceleration	0.173	Relative Respiration	0.139	R Knee Moment X	0.087
Ball Catch Known Release	R Knee Moment X	0.029	Abdomen Moment X	0.028	Hip Acceleration	0.027
Ball Catch Unknown Release	Hip Acceleration	0.042	R Knee Mom X	0.031	R Hip Moment Z	0.030

weaknesses included the small sample size, lack of direct abdominal muscle contraction measurement, and use of respirometer bands instead of direct inspiration volume measurement. We hypothesized that abdominal muscle contraction is a primary contributor to elevated IAP. We chose not to directly measure abdominal muscle activation with surface or fine wire EMG due to the high levels of measurement cross-talk that occur with EMG measurements in the pelvic and abdominal tissues (Keshwani and McLean 2013) along with motion artifact issues associated with EMG during highly dynamic tasks (Keshwani and McLean 2015). We decided to use abdomen and thorax biomechanical moments as a proxy for muscle activation in this study. While abdominal muscle activation is highly correlated with abdomen and thorax moments (Granata et al. 1999), there are many instances where abdominal muscle activation would not be captured by our motion capture approach. For example, abdominal muscle contraction when standing erect and motionless would not be measured because no net torque is applied to the abdomen model segment. Respiration was measured using piezoelectric bands instead of a volume-based method due to concerns that a volume-based system would obstruct key motion-capture markers and impact how participants would perform tasks with a mask attached to their face. The time-synchronicity of the motion capture and physiologic data was mainly dependent on participant's volitional control of their cough and step. Observation of participants performing the cough step provided confidence that such errors were minimal, possibly effecting the reported correlation and PLSR results, but unlikely to change the reported trends.

Despite the study shortcomings, our results tend to support our 4-element model of IAP generation. The RANOVA results showed that the participant performing the task was trending significant, which may indicate differences in general techniques employed between participants or may be a reflection of the differences in IAP ranges generated by various participants. Relative respiration and hip acceleration had the highest correlation with relative IAP in 15 of the 19 tasks in this study. Examination of the raw data indicated that the association between hip acceleration and IAP mainly occurred during initial ground contact for the box drop activity, during heel strike for the walking activities, and when initiating a sit to stand or ending a stand to sit maneuver. In all these instances there is a significant cranial acceleration at the hip, the magnitude of which are mirrored by

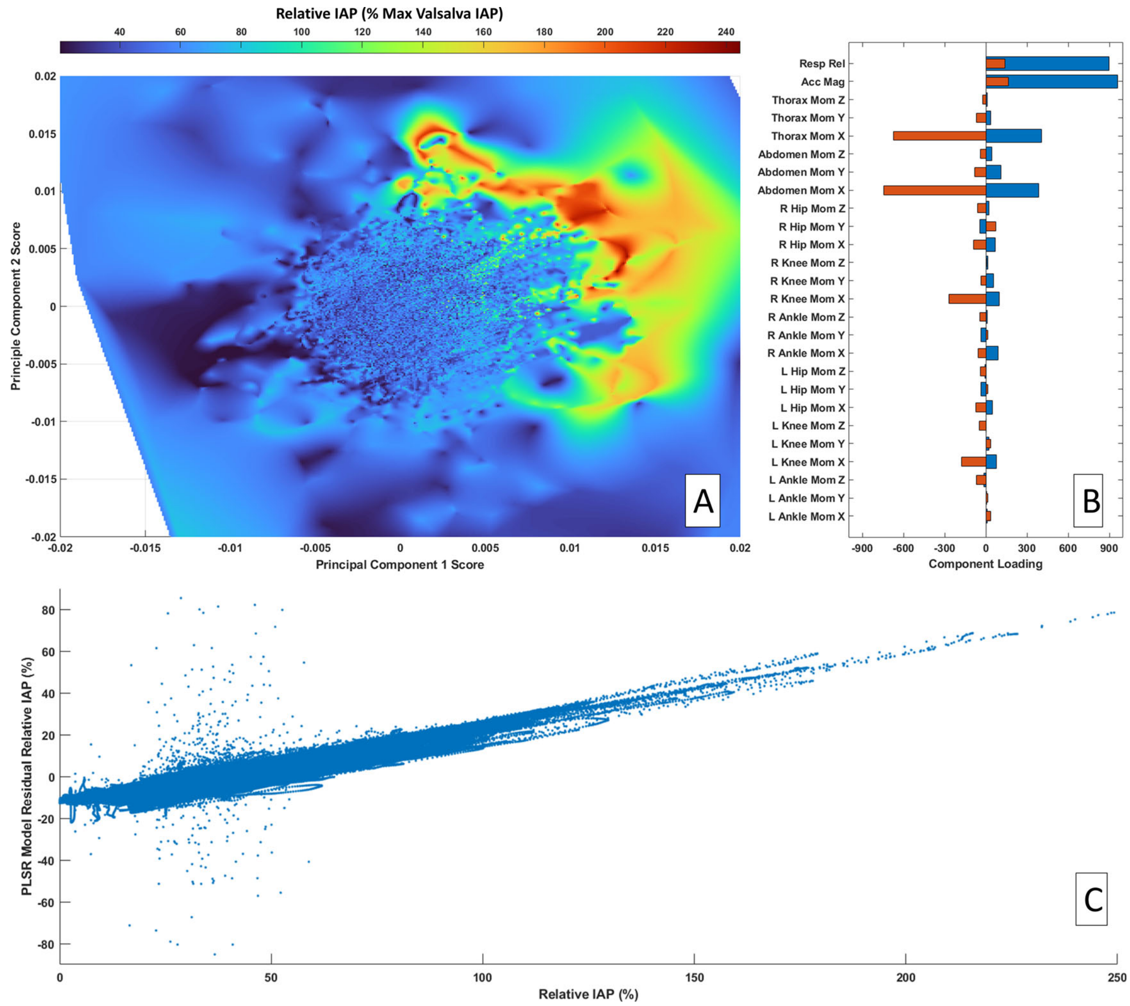

Figure 4. Partial Least Squares Regression Results. (A) Mean relative IAP heat map plotted against the first two PLSR principal component scores. Principal component scores are calculated as a linear combination of predictor variables weighted by component loadings. (B) Principal component loading bar graph showing the physiologic and biomechanical joint data predictor variable loadings for the first two principal components. The first principal component (blue) is most heavily loaded by the relative respiration and hip acceleration variables. The second principal component (red) is most heavily loaded by the abdomen and thorax flexion moment variables. Elevated IAP generally occurs when the first and second principal components are positive, indicating that elevated respiration volume, hip acceleration, abdomen and thorax flexion moments are likely primary contributors to elevated IAP. (C) Residuals of the PLSR model. The linear trend between the model residuals and actual relative IAP values may be indicative of an additional influencer on IAP generation not accounted for in our model, or may be due to our use of abdomen and thorax moments as a proxy for abdominal muscle contraction.

elevated IAP measured at the pelvic floor. Contrasting cranial accelerations, Figure 2 shows how gravity induces a static baseline pressure that significantly diminishes during freefall. Acceleration-based loading events occur often in daily activities, which may support the hypothesis regarding accumulated damage from repetitive sub-maximal loading events on pelvic structures (Vila Pouca et al. 2020).

Relative respiration was the highest correlate in tasks with extended skeletal loading, such as the 100% Jackson strength task, and both the front and side 10 kg lift tasks. Increased inspiration volume during these tasks may be used to stretch abdominal muscles to increase their length-tension relationship to aid in trunk stabilization or even spine offloading, as has been described previously (Essendrop and Schibye 2004; Cholewicki et al. 1999; Granata et al. 1999). The lack of direct correlation between IAP and abdomen or thorax moments in tasks that we would expect to find significant abdominal muscle recruitment, such as the fall recovery, ball catch, front-loaded walking tasks, likely indicates that abdomen and thorax moments are not a good proxy for abdominal muscle recruitment.

The PLSR model shows that hip acceleration, respiration volume, abdominal and thoracic flexion moments are most highly associated with elevated IAP. The linear trend in the PLSR residuals likely indicate there is an unaccounted factor contributing to elevated IAP.

The residuals trend may be due to either net balanced abdominal muscle contractions that are not captured by motion capture or a completely different mechanism not accounted for in our proposed 4-element model.

While the relative importance of abdominal muscle contraction relative to hip acceleration and relative respiration are difficult to ascertain due to our use of abdomen and thorax moments as a proxy, our results suggest that strategies to reduce hard impacts and inspiration volume during tasks may be just as vital as reducing abdominal muscle use when managing IAP to protect the pelvic floor. Momentum transfer of abdominal viscera during initial ground contact likely generates large forces on the pelvic floor, especially when considering the relatively small cross-sectional thickness of pelvic muscles compared to the mass of the organs they support. Inspiration volume more likely modifies the effect of other sources of IAP generation. Higher inspiration volumes stretch the abdominal wall and increase the length-tension relationship of abdominal muscles. While abdominal muscle contraction has long been known to be a primary contributor to elevated IAP, the role of inspiration volume and acceleration at the hip on IAP generation should be considered just as important in future research on IAP reduction strategies.

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