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Previous research suggests core strength training improves anticipatory postural adjustments, reducing one's risk of a fall, and stronger core muscles lead to faster reaction times. This study investigated whether core endurance and lower extremity strength relate to the time one needs to stabilize after being perturbed. An evaluation of ten participants while warming up determined each participant's transition speed between walking and running. While each participant walked at his/her transition speed, the belts were stopped randomly at an acceleration rate of 2.7 $m \cdot s^{-2}$ and ground reaction forces were recorded during balance recovery. Additionally, each participant completed a series of core endurance and lower extremity strength assessments, revealing a significant relationship only between hip extension and time to stability in the medial/lateral direction ($r = .784$, $p = .012$). Results contrasted expectations but match recent leanings in literature, suggesting isolated strength measures fail adequately to predict time to stability.

Keywords: Balance, core endurance, falls, lower extremity strength, perturbation

In 2013, the Center of Disease Control reported that in 2010 there were 2.3 million non-fatal injuries caused by falls in older adults (ages 65 and over) that required treatment in an emergency room, and of those, over 600,000 required hospitalization. The CDC recommends an exercise routine that has an emphasis on leg strength and increasing balance (CDC, 2013). They have a list of exercises on their website pertaining to things that can be done to increase balance, such as Tai-Chi, but there is only limited research supporting the ideas associated with these exercise methods. With numbers of falls getting higher and the population growing older, something must be done to prevent these falls from happening, or make the falls less severe.

This study looked at core strength and lower extremity strength, in relation to the ability to recover from a perturbation. In the field of Biomechanics there is an understanding that a stronger and more stable core will allow for better control of the lower extremities, which in turn could relate to a quicker recovery from a trip or a push. This research has the potential to provide insights that can be used to design better fall prevention programs for the geriatric community.

There has been research that made the connection between stronger core and faster reaction time, and stronger legs and faster recovery. However, there is also contradictory research that concluded that stronger legs made recovery slower. With this conflicting research, a project like this is even more important to try to find a consensus.

Methods

Participants

A sample of convenience was used, with 10 participants (6 female, 4 male, age =

19-34 years, height = 1.71 ± 0.07 m, mass = 68.3 ± 8.5 kg) volunteering for the study. They were all healthy, active, non-smokers, and had no history of musculoskeletal injuries in the last six months. Participants were recruited from campus facilities, and graduate Sport and Exercise Science courses. Each participant set up a time beforehand, and came into the Biomechanics Lab in Gunter Hall at the University of Northern Colorado for an hour of testing. Although the purpose of this study was to determine factors that could help a member of the geriatric community recover better, only healthy young adults ages 18-35 were considered. This is due to a variety of reasons, first of which being the procedure was rigorous for someone of average athleticism and for someone who is older and less athletic, it would be very difficult, and potentially dangerous. However, studying a young, healthy population would provide insights into a "normal" recovery pattern from the perturbation that has implications on geriatric populations, particularly with regards to the deficits in the population. Thus, this study was a first step into trying to understand how a healthy, intact system recovers balance with future studies focused on older populations who may exhibit balance deficits.

Data Collection Procedures

Participants set up a time beforehand with the Primary Investigator, and blocked out a two-hour session in the Biomechanics Lab (though most testing sessions took less than one hour). When the participants first came into the lab, they were given two copies of the Informed Consent Form, one for them to sign and keep, and one for the lab records. After they read the Informed Consent, they were asked if they had any questions. Then they signed and dated both copies, and so did the Primary Investigator. Basic anthropometric measurements were then taken: height (cm), weight (lbs.), and foot dominance (right/left). Foot dominance was determined by asking participants which foot they would prefer to use to kick a soccer ball as far as possible.

Warm Up

Participants were then led to the instrumented treadmill in the middle of the lab. The treadmill is built in to the ground, and has no handlebars, so they were attached to a chest harness, which was attached to the ceiling, to catch participants if a fall occurred. Each participant then performed a ten-minute warm up on the treadmill at a comfortable walking speed (set by their preference). Abad, Prado, et al. in 2011, suggested that strength measures increased by 8.4% when they included a general warm-up on top of a motion specific warm up for that was being tested, which is why the ten-minute warm up was utilized in this study. The warm-up also helped ensure that all participants were comfortable walking on the treadmill prior to the perturbation protocol.

During the last three minutes of the warm up, the participant's transition speed was determined. Transition speed was defined by the speed at which the participant went from walking to jogging. To find this, the belt speed was slowly increased (in 0.10 m/s increments), and the participant was instructed to try to walk for as long as they could. When the participant transitioned from walking to jogging, the speed was marked. The belt speed was increased for 30 seconds while they were jogging, and then the participant was told that the belt was going to start slowing down, and that they should try to start walking as soon as they could. The belt was slowed at 0.10 m/s increments, and the speed in which the participant started walking was again marked. The belt was brought back down to the participant's comfortable walking speed, and then slowly stopped after the participant was warned. The average of the two transition speeds was taken, and that was designated as the test speed.

Perturbation Protocol

The perturbation protocol was explained to the participants while he/she took a break after the warm-up. Once back on the treadmill (in the harness), the belt was accelerated to the participant's transition speed as determined during the warm up. Each participant walked at this transition speed for a random amount of time (ranging 5-10 minutes). Randomly, the treadmill belts were stopped abruptly with an acceleration rate of 2.7 $m \cdot s^{-2}$. Ground reaction forces (GRF; 2000 Hz) were collected for 25 seconds during each perturbation. The GRFs were recorded from two force plates positioned directly beneath the treadmill belts. GRF recordings began approximately 5 seconds prior to the belts being stopped and continued for an additional 20 seconds while participants recovered their balance. Once the belts stopped, it was common for participants to stumble. They were asked to maintain a stationary stable position as quickly as possible once the belts stopped. The entire procedure was then repeated four more times for a total of five trials for each participant.

Isokinetic Strength Measurements

The second set of tests performed was the isokinetic lower extremity strength measurements. These tests were taken on the Biodex in the lab, which is a dynamometer that can perform both isokinetic and isometric strength measurements. Isokinetic measurements were chosen for this study because when walking, the joints are moving, not staying static. Measurements were taken at the hip, knee, and ankle joints, all on the non-dominant leg. The non-dominant leg was used because of laterality, which says that the dominant leg is used for strength, and the non-dominant leg is used for stability. Each participant was given the three tests in a pseudo-randomized order to remove the variable of fatigue.

For each strength measure, the participant was strapped in to the Biodex (using specifications indicated below), and range of motion was determined. Specifications came from Biodex Medical Systems Inc. and gravity correction was determined. The participant then performed three sets of five flexion/extensions for each joint, with 30 seconds rest in between. The first set was at 50%, and was used as a warm up. The second set was performed at 75%, to continue the warm up. The last set was performed at 100%, with verbal encouragement from the Primary Investigator.

The hip extension and flexion strength was taken in the standing position. The participant stood on the Biodex platform and had the thigh pad attached proximal to the knee. The dominant leg stayed straight for support, and the Biodex stand was available for balance if needed, but not to propel the limb. The Biodex was set to 90 degrees/second.

For the knee flexion/extension test, the participant was seated, and strapped in to seat via a chest harness, and the non-dominant leg was strapped down at the thigh. The lower leg was strapped in to the Biodex arm, with the pad at a comfortable distance from the ankle. The Biodex was set to 30 degrees/second.

For the ankle planterflexion/ dorsiflexion test, the participant was seated, and strapped in to the seat via the chest harness, same as the knee test. The non-dominant leg was supported by a stand attached to the chair, to raise the leg in line with the Biodex arm. The leg was strapped in to the stand, and then the foot was attached to the Biodex arm via Velcro straps at the top of the foot and at the joint. The Biodex was set to 30 degrees/second.

Core Endurance

The final test was the core endurance exercises. Each participant performed four different static core endurance exercises in a pseudo-randomized order to void the variable of fatigue. Participants performed a right plank, left plank, isometric trunk flexor exercise, and an isometric trunk extensor exercise, all until failure, based on a study by Leetund et al. in 2004. Time was measured with a stopwatch, and then recorded. They were given a break in between measures if needed.

The right/left plank test was administered on a tumbling mat. The participant was told to lay on their side, with their feet stacked. When they were ready, the participant would use their forearm to balance as they lifted themselves off the ground. They placed their non-supportive arm across their chest. When any part of the participant's body touched the mat, the test was terminated.

The isometric trunk flexor exercise was also administered on the tumbling mat. Participants would sit up in a crunch-like position, with their feet on the ground, and knees bent. A plywood triangle was placed behind their back, and they would lean back onto the board. When they were ready, the board was removed, and the time started. The participant had to hold the same position that the board put them in, until failure.

The last core endurance test was the isometric trunk extensor exercise. This test was administered on a medical/therapy table. The participant would lay face down on the table with their hips and above hanging off. They were given a chair if requested to rest on before the test started. Two straps were used at the thigh and calf to tightly secure them to the table. The straps were adjusted to the participant's comfort. When the participant was ready, the chair was removed, and they brought their upper body up until it was parallel with the ground, with their arms across their chest. They would hold this position until failure.

At the end of the testing session, participants were allowed to ask any follow up questions they might have. They were given their copy of the informed consent, with the contact information for the Primary Investigator, Co-Author, and the Office of Sponsored Programs, in case they had questions later on.

The only information that had the participant's name on it was the informed consent, which was kept with the Primary Investigator. Any subsequent information was labeled by their participant number, and was kept on a password-protected computer, or in the locked Biomechanics lab.

Data Analysis Procedure

Strength Measures

The first step of data analysis was determining strength values. Numerical values were taken straight from the core endurance times and tabled. To find the lower extremity strength values, the last set for each joint for each participant was exported. The peaks for each repetition were then found from each set of data in each direction. The peaks were then averaged for each participant, and tabled.

From the lower extremity strength measures for individual joints, total leg strength was determined (in both the flexion and extension directions). This was an added variable that allowed for the analysis of the whole leg, to make up for any muscular discrepancies that may have existed within the individual.

The lower extremity strength measures were then normalized.

The original measurements were given in foot-pounds, so they were divided by the participant's height and weight to give a number without units, which could be compared more easily to others.

Determining TTS

Determining TTS ended up being more challenging than the original procedure suggested. The timing of the belt was not connected to the Vicon system, which meant that there was no way of determining time based on the force data as it was. First, the GRFs were collected at 2000 Hz, and were determined in the medial/lateral (Fx), anterior/posterior (Fy), and vertical (Fz) directions (see Figure 1).

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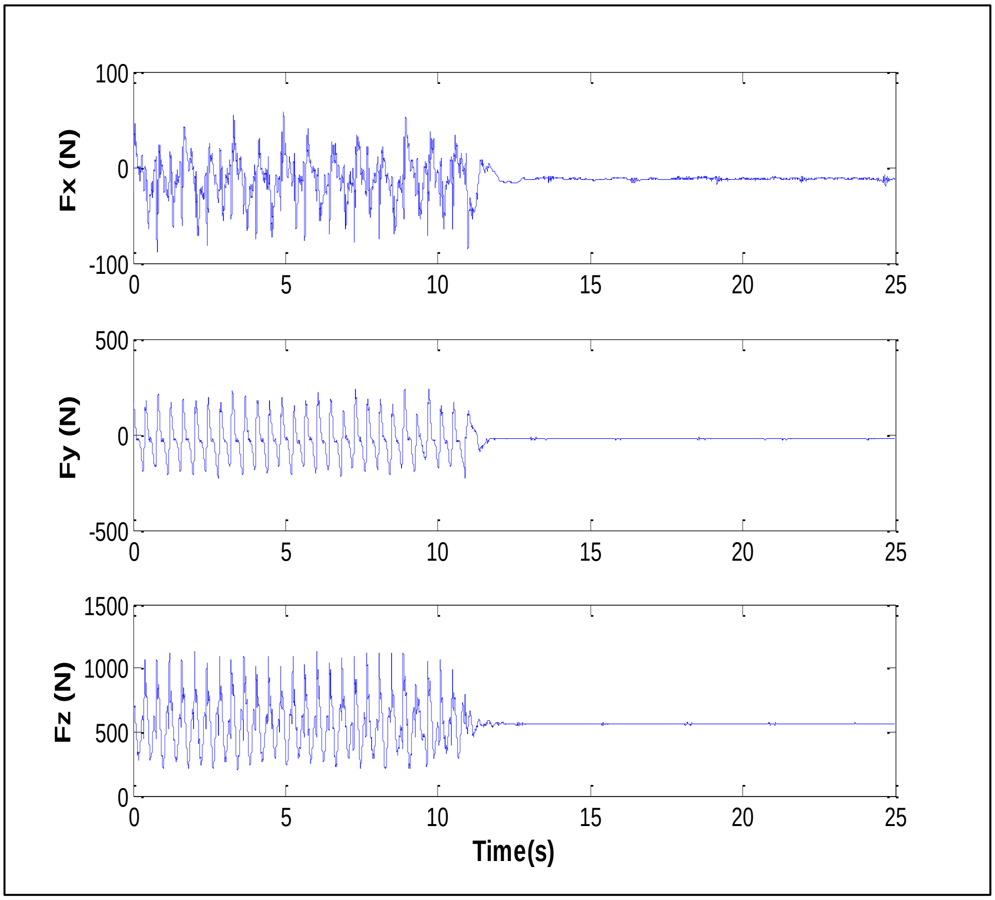

Figure 1. Example GRFs in the medial/lateral (Fx), anterior/posterior (Fy), and vertical (Fz) directions.

The velocity of the center of mass was found by using Newton's second law to first get the acceleration of COM. From there, the acceleration data was integrated with respect to time, to get velocity. The integration constant for the vertical (Fz) and medial/lateral (Fy) were assumed to be zero, and the anterior/posterior (Fx) direction it was assumed to be the treadmill velocity (see Figure 2).

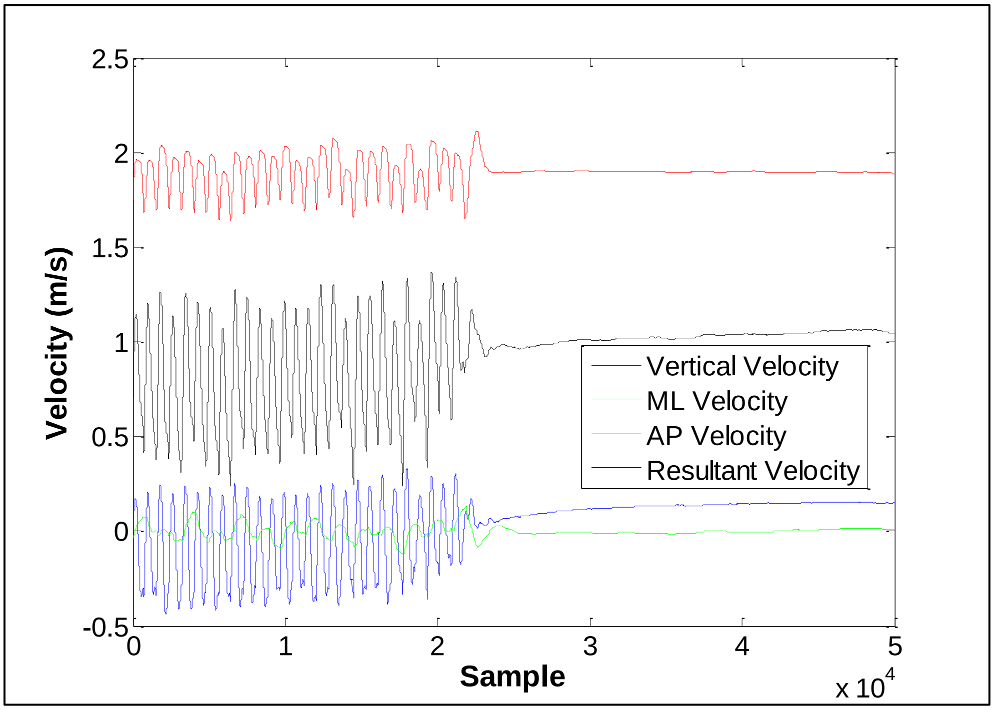

Figure 2. Example of COM velocities in the ML, AP, and vertical directions.

Within the program, the velocities were lined up vertically (as seen above). From there, the point where the COM was perturbed was determined by finding the point in which the normal velocity was disturbed. The point in which the velocity changed was the same in each of the three directions. This was repeated for each of the participant's five trials.

This gave the perturbation a starting point, and the next step was to determine when the participant came to stability. Based on the procedure from a previous study (Colby, Hintermeister, Torry, & Steadman, 1999), and the way stability was determined varied in each of the three force directions.

In the medial/lateral direction, stability was determined by first taking the average of the forces produced in the last seconds of the trial, when the participant was standing perfectly still. This was the force they created when they were stable, which was used as a standard to find the TTS. The standard deviation was found from this value. TTS was found by finding when the sequential average of the forces in

the medial/lateral direction reached +/- 25% of that standard deviation (SD). An example of this graph can be seen in Figure 3.
TTS was found in the anterior/posterior direction by taking the average of the last few seconds of stability, and then the standard deviation was calculated. The standards were the same as the medial/lateral direction (+/- 25% of SD), but when TTS was calculated, the times were coming out much smaller than the other two directions, causing confusion. The threshold was changed to +/- 10% of the SD, to make it more sensitive. The values for the TTS were comparable after the adjustment. An example of this can be seen in Figure 4. The procedure to find TTS in the vertical direction was similar, except that body weight was used. The threshold was +/- 3% of the person's body weight. An example of the TTS graph can be seen in Figure 5.

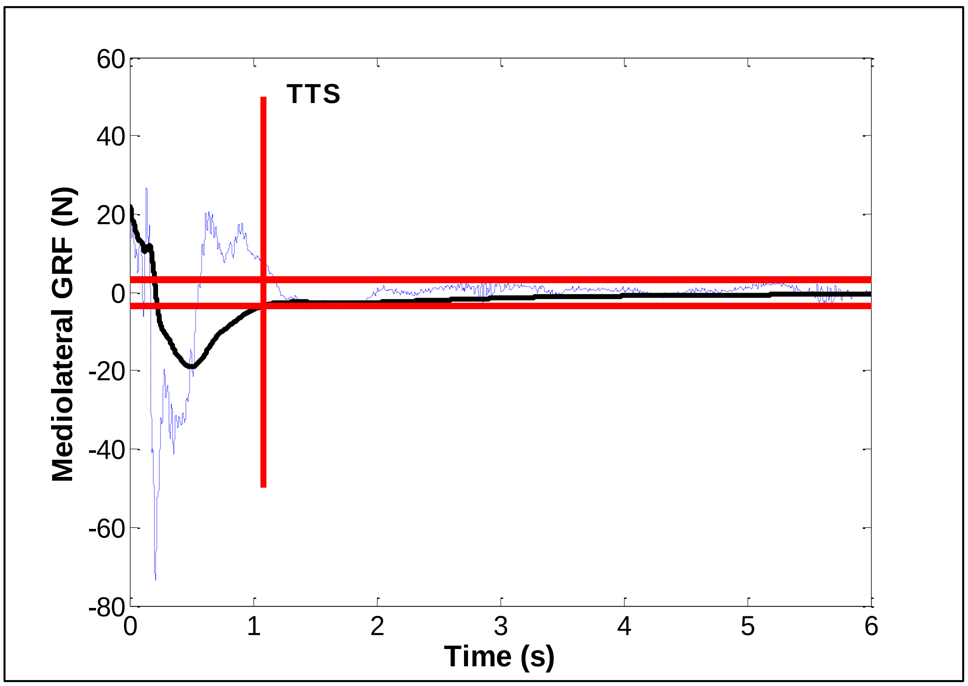

Figure 3. Example of TTS in the medial/lateral direction. The red parallel lines are the +/- 25% of SD values. The blue line is the true force values, and the black line is the sequential average. The red perpendicular line is the sequential average hit the SD threshold, and stability was found.

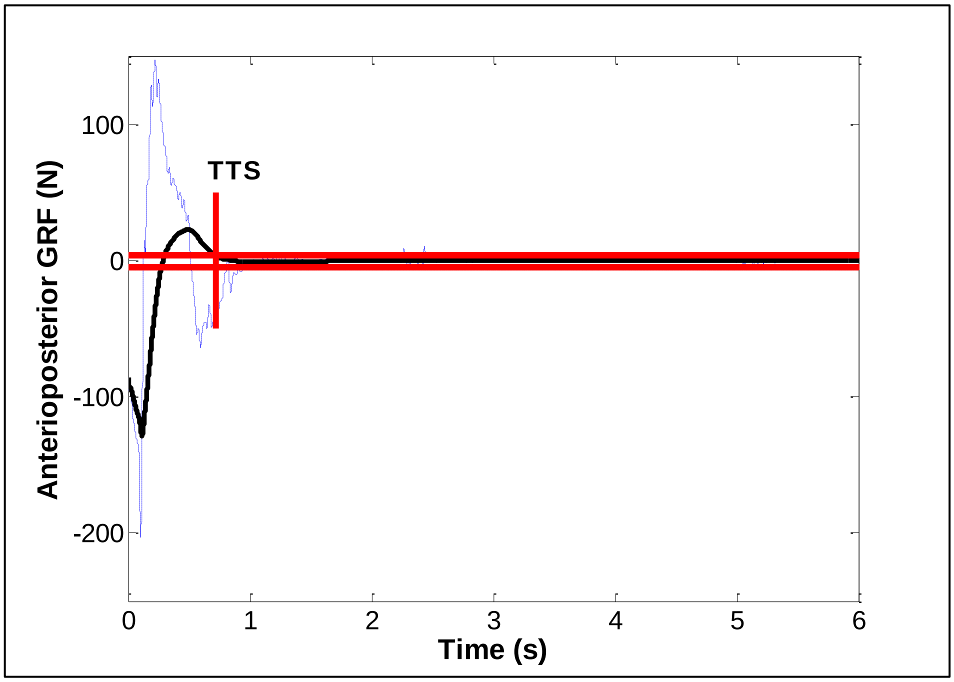

Figure 4. Example graph of TTS in the anterior/posterior direction.

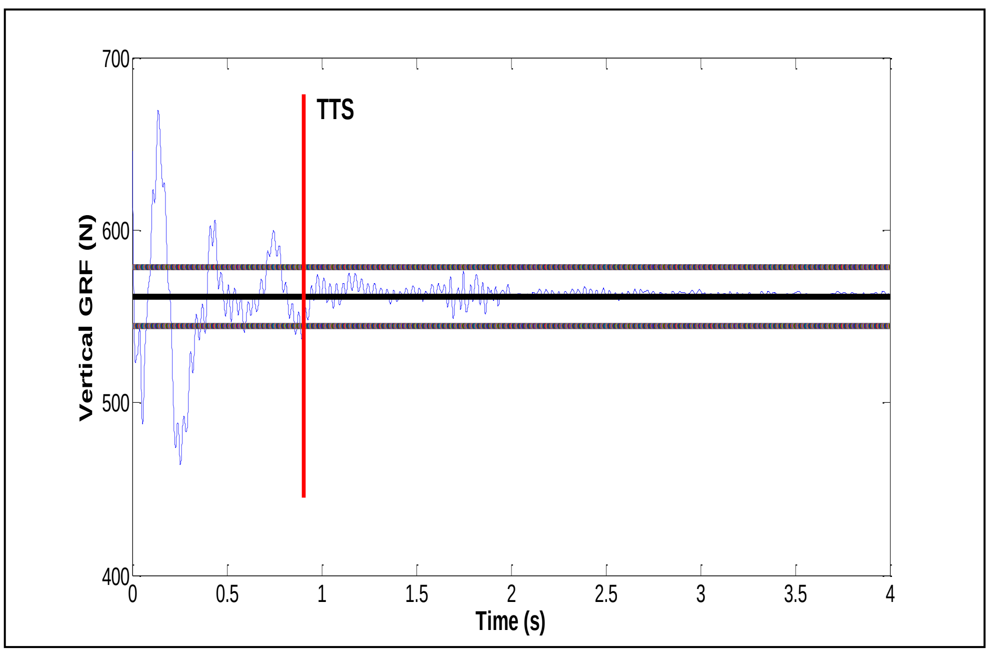

Figure 5. Example graph of determining TTS in the vertical direction.

TTS was determined in each of the three directions for each trial of each individual. Any outliers were removed, and the average was taken for each participant's TTS in each direction. From there, the averages were tabled, and a group mean and standard deviation was determined. From the table graphs were made to look at the relationships between TTS and the variables. The 17 different variables that were analyzed were: 1) height, 2) weight, 3) mass, 4) transition speed, 5) right plank time, 6) left plank time, 7) isokinetic trunk flexor time, 8) isokinetic trunk extensor time, 9) plank average, 10) hip flexion, 11) hip extension, 12) knee flexion, 13) knee extension, 14) ankle plantarflexion, 15) ankle dorsiflexion, 16) leg extension total, and 17) leg flexion total. Once the graphs were made, the 51 different relationships were tested using Pearson Product Moment Correlations ($\alpha = 0.05$). A chart was made (see Figure 6) and R-values were determined for each relationship.

Results

During data analysis, one participant (CJH06) was eliminated due to outlying results in the core endurance measures. Therefore, an n of nine was used for data analysis.

After running the Pearson Product Moment Correlations, it was determined that only one variable was significant when looking at factors that could be predictors of TTS, with that being the relationship between hip extension and TTS in the medial/lateral direction ($r = 0.784$).

Discussion

The only significant relationship was the relationship between hip extension and TTS in the medial/lateral direction ($r = 0.784$). This is a very strong positive correlation that suggests the stronger the hip extension muscles (gluteus maximus and hamstrings), the greater the amount of time it took participants to stabilize after being perturbed.

One explanation as to why stronger hip extensors might relate to a slower recovery comes from a Pavol in 2002. They found that those with faster walking speeds and longer steps had greater plantarflexion and knee extension strength, but then they were also the majority of those who fell in the study. They concluded that those who have a faster normal gait are at an increased risk of falling, and those with stronger legs have a faster gait. Therefore, those with stronger legs fall more. In the current study, there was not a relationship transition speed and time to stability. Though, there was a significant relationship between transition speed and leg flexion strength (leg flexion total and hip flexion).

A lack of significant results (aside from the one) can be interpreted as a result of its own. It cannot be determined based on this study that core training would help/hinder ability to recover. It can also not be determined that lower extremity strength training would help/hinder the ability to recover.

It can be determined that looking at joints at an individual level is not an effective way to determine TTS. The single joint strength measurements are not enough to predict TTS, and thus a different method of measurement should be used in the future. Based on this research, it is suggested that instead of looking at joints individually, the whole body should be considered instead.

There is an equilibrium triad, which is composed of the three different receptors that tell the body where it is in space: proprioceptors (Golgi Tendon Organs and muscle spindles, which provide the brain information about joint angles, muscle length, and muscle tension), vestibules (in

		Fx_TTS	Fy_TTS	Fz_TTS
Fx_TTS	Pearson Correlation	1	.633	.760*
	Sig. (2-tailed)		.067	.017
Fy_TTS	Pearson Correlation	.633	1	.623
	Sig. (2-tailed)	.067		.073
Fz_TTS	Pearson Correlation	.760*	.623	1
	Sig. (2-tailed)	.017	.073	
Rt_Plank	Pearson Correlation	.467	.335	.243
	Sig. (2-tailed)	.205	.379	.528
Lt_Plank	Pearson Correlation	.229	.192	.104
	Sig. (2-tailed)	.553	.622	.790
Plank_AVG	Pearson Correlation	.342	.260	.169
	Sig. (2-tailed)	.368	.499	.664
Trunk_Flex	Pearson Correlation	.338	.058	.495
	Sig. (2-tailed)	.373	.883	.176
Trunk_Ext	Pearson Correlation	.418	.153	.500
	Sig. (2-tailed)	.263	.695	.171
Trunk_AVG	Pearson Correlation	.403	.109	.535
	Sig. (2-tailed)	.282	.781	.138
Hip_Ext	Pearson Correlation	.784*	.565	.377
	Sig. (2-tailed)	.012	.113	.317
Hip_Flex	Pearson Correlation	-.077	.095	-.213
	Sig. (2-tailed)	.845	.808	.582
Knee_Ext	Pearson Correlation	.042	-.111	-.196
	Sig. (2-tailed)	.914	.776	.614
Knee_Flex	Pearson Correlation	.517	.323	.396
	Sig. (2-tailed)	.154	.397	.292
Ankle_DF	Pearson Correlation	-.296	-.175	-.094
	Sig. (2-tailed)	.440	.653	.809
Ankle_PF	Pearson Correlation	.239	.152	.292
	Sig. (2-tailed)	.536	.697	.445
Leg_Ext_TOT	Pearson Correlation	.140	.019	-.061
	Sig. (2-tailed)	.720	.961	.876
Leg_Flex_TOT	Pearson Correlation	.242	.227	.126
	Sig. (2-tailed)	.530	.557	.747
Trans_Speed	Pearson Correlation	.126	.361	.179
	Sig. (2-tailed)	.746	.340	.644

Figure 6. Pearson Product Moment Correlations Results. (* means correlation is significant at the 0.05 level, ** means correlation is significant at the 0.01 level)

the ear, provides information about the position of the body), and vision (reference points for the body. The current study did nothing to perturb any of the three systems in particular, which may have led to a lack of results. By perturbing one or more of those systems directly, a better result may be found.

The small sample size may have played into the lack of diverse results. A participant pool of only healthy college-aged students was used due to various factors. Healthy participants of a younger age are less likely to fall, meaning that there is less of a risk in testing them. Also, being on a college campus means that the younger population is more readily available. Because of this specific population, there may have been too little variability, even though the participants were taken from different lifestyles.

Future Research

In the future, research should be aimed toward looking at the person as a whole instead of the smaller pieces. One way to potentially do that is to follow the suggestions by the CDC (CDC, 2013). They suggested doing a balance based exercise routine (e.g. yoga, tai-chi, Pilates) to prevent falls. One possible future study could be to look at recovery ability of those who do a balance based exercise routine, versus someone who exercises regularly but not a balanced based routine, versus someone who does not exercise.

Another way to approach the study is to look at how the participant perceives the world around them. There is feedback system that goes into everything that people do, which could be a factor when falling/recovering. This is the equilibrium triad discussed previously. A suggestion would be to blindfold the participant to remove the visual receptor, then perform the same perturbation simulation, and see how it changes, and whether or not the strength measures have a larger impact then. A way to perturb the proprioception of a participant could be to place them on an uneven surface, or a surface that moves in multiple directions.

Another possible study could be to actually look at a geriatric sample. The procedure would have to be manipulated to make it safer and easier for a compromised participant, but it might lead to clearer results. Within that population, a longitudinal study could also be considered. By working with three different groups (a control, those who do a structured balance based exercise program, and those who exercise, but not balanced based) and create a training program that can be monitored, possible conclusions can be made about the types of exercise that should be done to prevent falls.

Strong adults and weak older adults fall at different stages in a perturbation, as determined by watching gait mechanics in the lab (Pavol, 2002). A lack of gait mechanics analysis in the study (as well as a lack of geriatric participants) means that this study cannot speak to that topic, but it would be a future step.

Another possible aspect to analyze would be a different plane of motion. Hip strength was measured for flexion and extension, but during recovery, hip abduction and adduction occurred. Taking measurements on the Biodex for abduction and adduction may reveal more relationships that may provide better insight to recovery. Ankle rotation and knee medial and lateral rotation may also be important to test.

Conclusion

While the relationship between hip extension and TTS does not reflect past findings, it does side with what has been found recently in other studies within the UNC Biomechanics lab, and what current research is uncovering. Isolated single joint measures of muscle strength do not appear to be related to one's ability to recover from a perturbation. Given that postural stability and balance are dependent on three sensory input systems – somatosensory, vestibular, and vision – it is more likely that perturbations to these specific systems will provide further insights in to recovery abilities.

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