人體動作平衡控制
與
梯子設計之人因考量

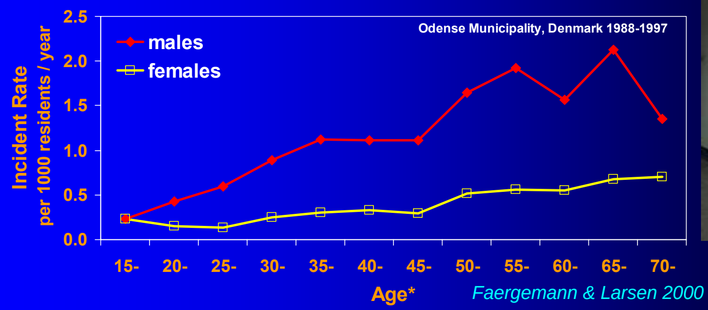
楊秉祥
國立交通大學　機械工程學系

2

Falls from Ladders

- More than 17% of occupational fatal falls are from ladders (U.S. Bureau of Labor Statistics, 2001).
- More falls occur from ladders in non-occupational settings (Tsipouras et al 2001).

Non-occupational ladder/scaffold falls



Faergemann & Larsen 2000

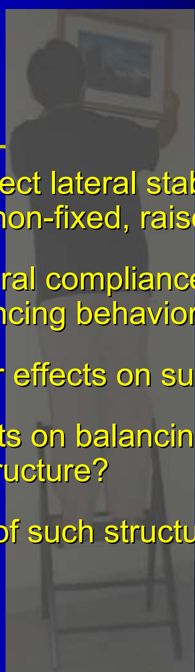
3

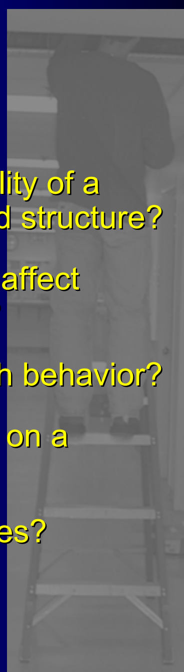
Falls from Ladders

- More than 17% of occupational fatal falls are from ladders (U.S. Bureau of Labor Statistics, 2001).
- More falls occur from ladders in non-occupational settings (Tsipouras et al 2001).
- 20-27% ladder fall injuries need to be hospitalized for 7-8 days (Björnstig and Johnsson 1992; Faergemann and Larsen 2000).
- Ladder falls cause serious injuries in older adults (Björnstig & Johnsson 1992; Faergemann & Larsen 2000,2001).
- Lateral falls are the most frequent cause of injuries of stepladder accidents (Björnstig & Johnsson 1992).

4

Research Questions





- What are the factors that affect lateral stability of a human standing on a rigid, non-fixed, raised structure?
- How does the lateral structural compliance affect subjects' stepping and balancing behavior?
- Are there any age or gender effects on such behavior?
- Are there any learning effects on balancing on a laterally-compliant raised structure?
- Can we improve the safety of such structures?

Research Outline

- Feasible lateral weight transfer on rigid structures
- Effects of unexpected structural compliance on stepping and balancing behavior
- Adaptive changes of stepping movements
- Effects of stepping strategy on system stability

Significance of Study

- Insights needed to reduce fall-related injuries caused by falls from stepladders/chairs, especially in older adults.
- Developing the first study of the interaction of age and structural compliance on postural stability of stepping and balancing behavior on a raised structure.

7

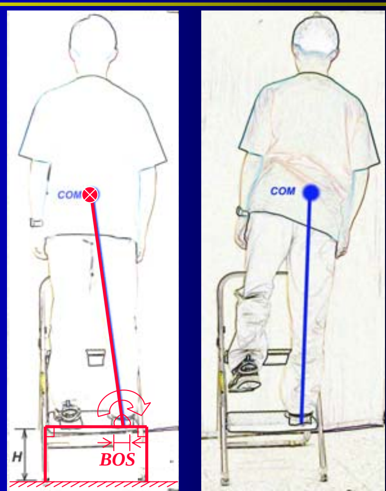
Research Outline

- Feasible lateral weight transfer on rigid structures
- Effects of unexpected structural compliance on stepping and balancing behavior
- Adaptive changes of stepping movements
- Effects of stepping strategy on system stability

8

Methods – Biomechanical model

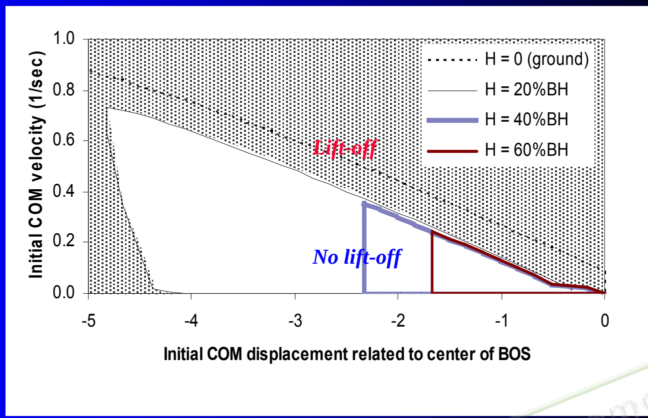
- Lateral weight transfer movements
- Structure: rigid, planar, inverted “U” structure
- Human body: fixed-length single-segment inverted pendulum
- Rail *“Lift-off”*



Frontal plane

9

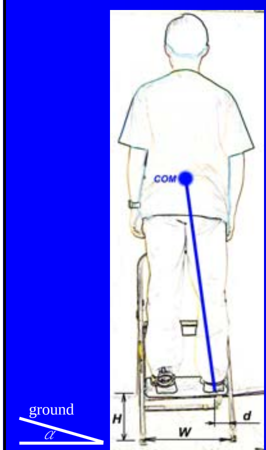
Results – Effects of tread height

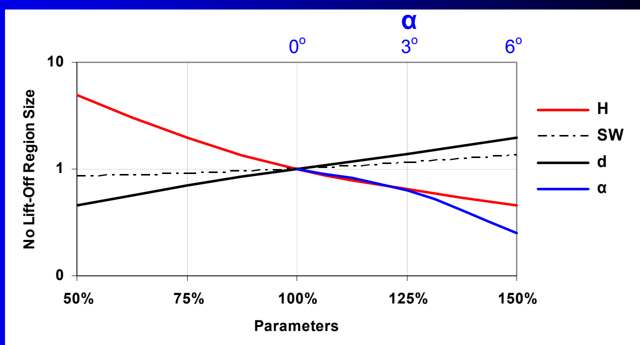


SW=15%BW, d=1/4W, α =0

10

Sensitivity Analysis



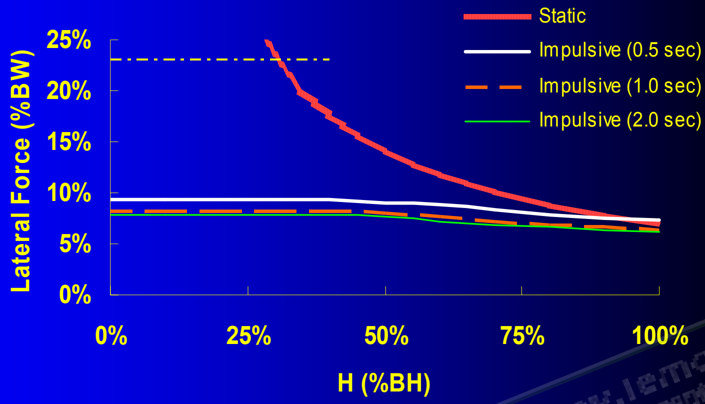


Operating point (100%): H=40%BH, SW=15%BW, d=1/4W, α =0

11

Max. Allowable Lateral Force

ipsilateral pulling / contralateral pushing



12

Conclusions

- Feasible lateral movements were identified.
- Most sensitive factors are tread height, ground inclination angle, and stance-foot position.
- Safety suggestions:
  - Slow weight shift
  - Avoid extreme lateral foot placement, especially on a parallel-sided structure
  - “A”-shaped stepladders need larger included angles between rails than suggested by ANSI standards

13

Research Outline

- Feasible lateral weight transfer on rigid structures
- Effects of unexpected structural compliance on stepping and balancing behavior
- Adaptive changes of stepping movements
- Effects of stepping strategy on system stability

14

Hypotheses

- Primary null hypothesis
  - *Unexpected* structural compliance of a raised structure does not affect the stepping and balancing behavior.
- Secondary null hypothesis
  - There is no age or gender difference in this behavior.

15

Experiment

- Subjects: 30 Healthy Adults (10 in each group).

	Age (yrs)	BH (cm)	BM (Kg)
Young Females (**YF**)	25.2 (2.0)	160.1 (5.1)	53.2 (5.5)
Young Males (**YM**)	26.0 (2.5)	168.5 (1.7)	71.4 (11.6)
Older Males (**OM**)	72.2 (2.6)	168.7 (4.3)	69.1 (8.1)

Note: no significant BH (p=0.92) and BM (p=0.74) differences between YM and OM

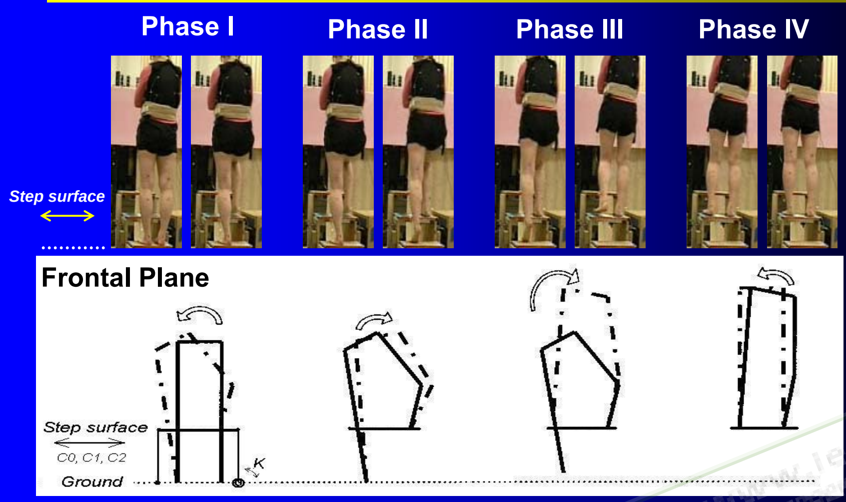
16

Experiment

- Subjects: 30 Healthy Adults (10 in each group).
- Task: Forward stepping up onto a 7”-high step
  - 3 covertly assigned structural compliance x 6 trials
  - Compliance: C_0<0.01 mm/N, C_1=0.1 mm/N, C_2=0.2 mm/N
- Measurements (at 100Hz)
  - Body kinematics – 10 IRED (Optotrak 3020)
  - Ground reaction forces (AMTI Force Plates)
  - Normal forces (F-scan pressure sensors)

17

Phases of Stepping Movements



Results

First trial (N=30) on each value of structural compliance

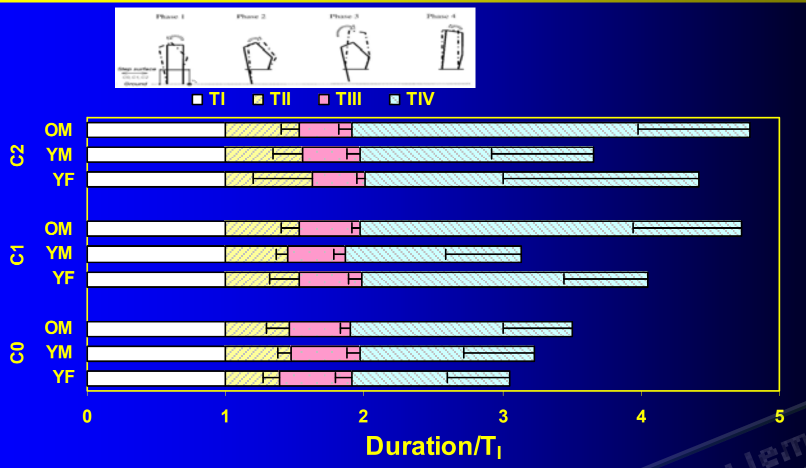
1 C_0 trials | C_0 6 trials … 1 C_1 trials | C_0 6 trials … 1 C_2 trials

Rigid — 0.1 mm/N — 0.2 mm/N

[C0 C0 C0 C0 C0 C0] [C1 C1 C1 C1 C1 C1] [C0 C0 C0 C0 C0 C0] [C0 C0 C0 C0 C0 C0] [C2 C2 C2 C2 C2 C2]

19

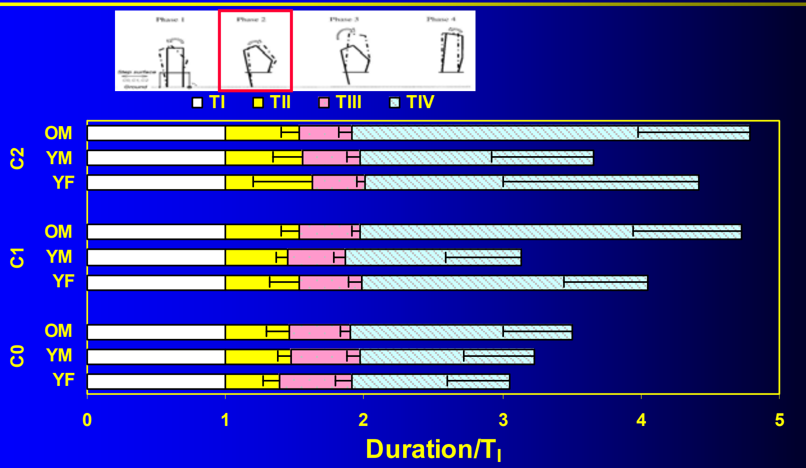
Effect of Compliance on Duration



C: p=0.002; Age: p<0.001; Gender: p=0.004

20

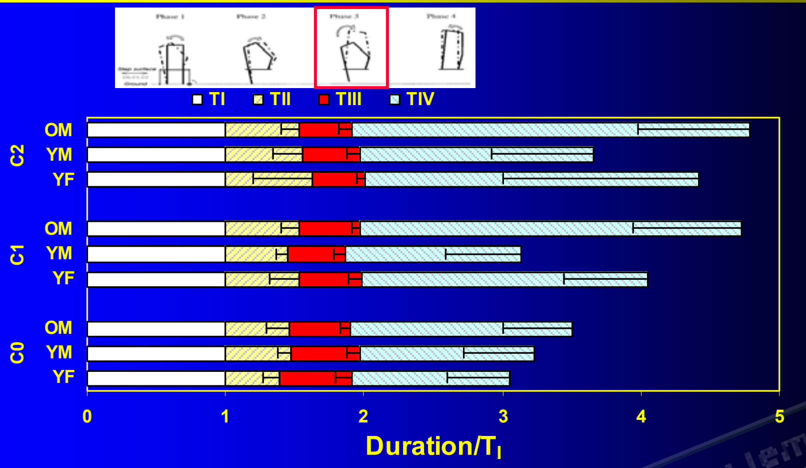
Duration in Phase 2



Ph2: C: p=0.2; Age: p=0.63; Gender: p=0.68

21

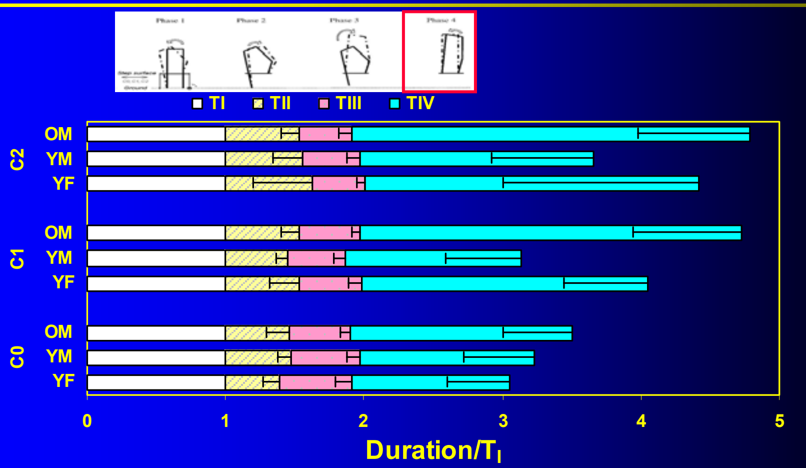
Shorter Unipedal Support Phase



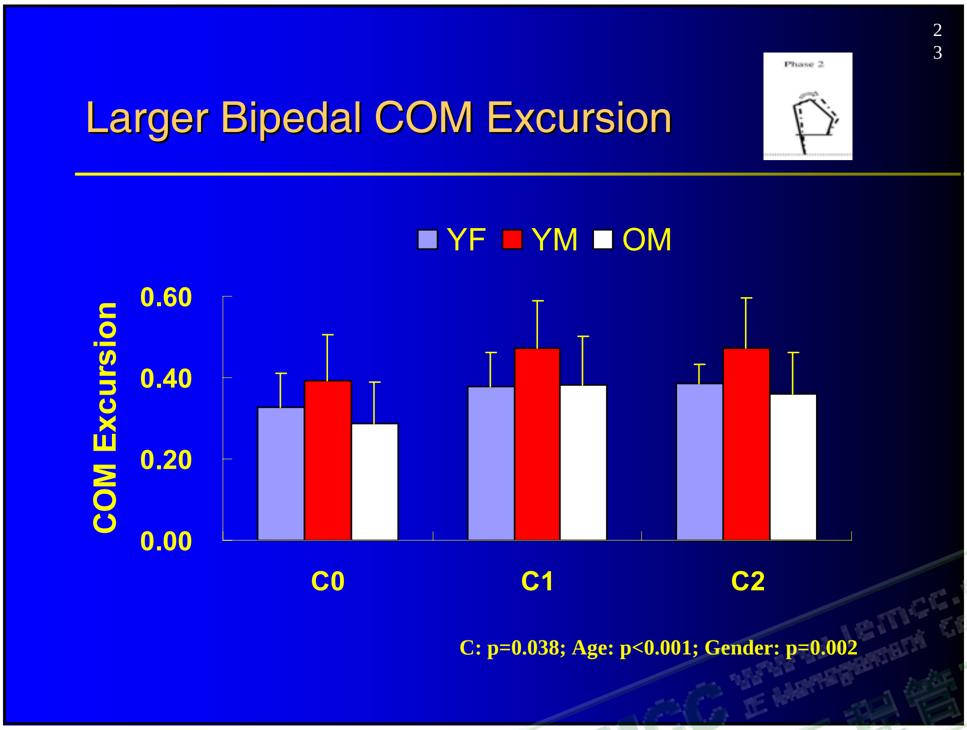
Ph3: C: p=0.029; Age: p=0.26; Gender: p=0.75

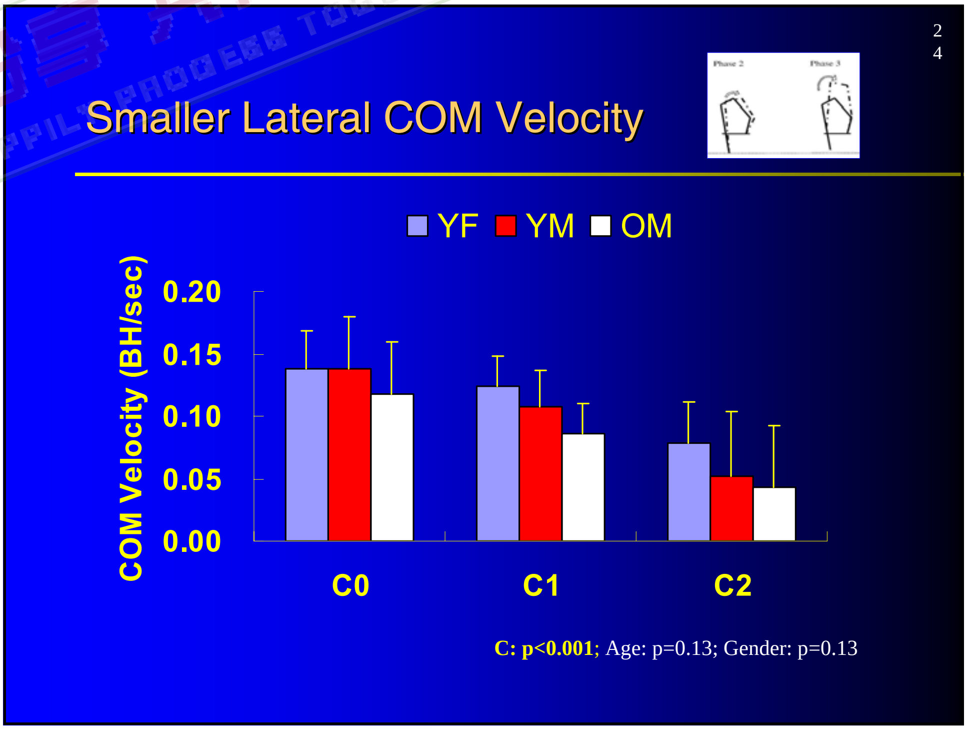
22

Longer Lateral Balance Recovery

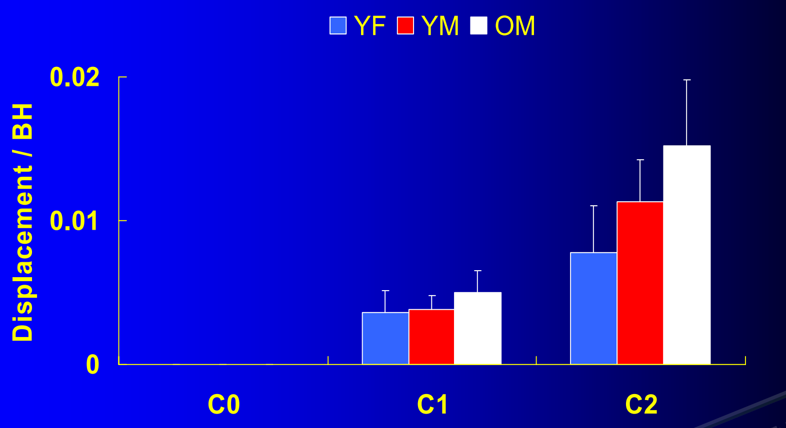


Ph4: C: p<0.001; Age: p<0.001; Gender: p=0.02


23
Larger Bipedal COM Excursion
Phase 2
YF YM OM
COM Excursion
0.60
0.40
0.20
0.00
C0
C1
C2
C: p=0.038; Age: p<0.001; Gender: p=0.002


24
Smaller Lateral COM Velocity
Phase 2
Phase 3
YF YM OM
COM Velocity (BH/sec)
0.20
0.15
0.10
0.05
0.00
C0
C1
C2
C: p<0.001; Age: p=0.13; Gender: p=0.13

Lateral Structural Displacement



C: p<0.001; Age: p=0.02; Gender: p=0.03

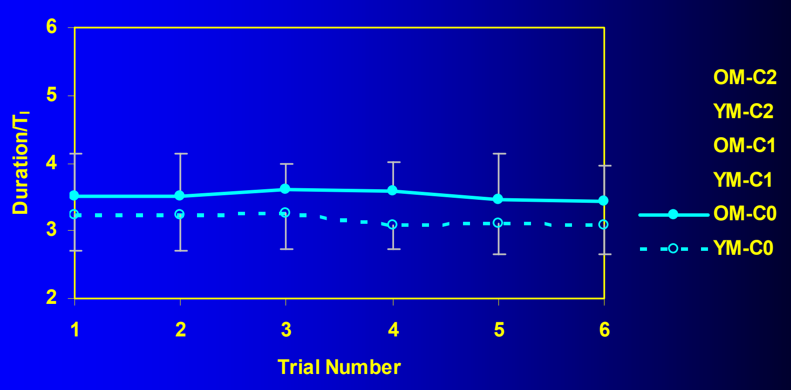
Conclusions

- Lateral structural compliance adds 15% time for YM, 33-45% for YF, and 35-37% for OM to complete one step-up movement.
- Healthy adults were able to identify the presence of the structural compliance as they first step onto a raised structure.
- Older males needed longer time than did young adults to step up and balance on a raised structure with “unexpected” lateral compliance.

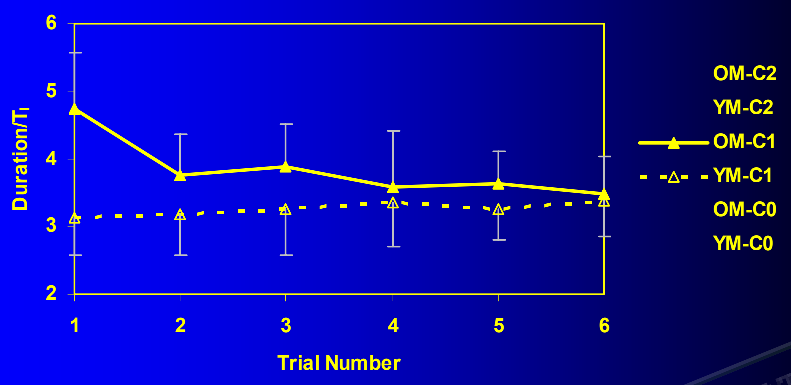
Research Outline

- Feasible lateral weight transfer on rigid structures
- Effects of unexpected structural compliance on stepping and balancing behavior
- Adaptive changes of stepping movements
- Effects of stepping strategy on system stability

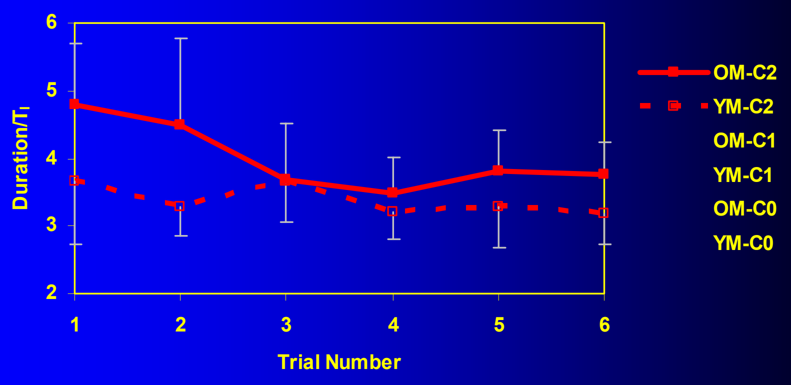
Results – Duration vs. Trial on C0

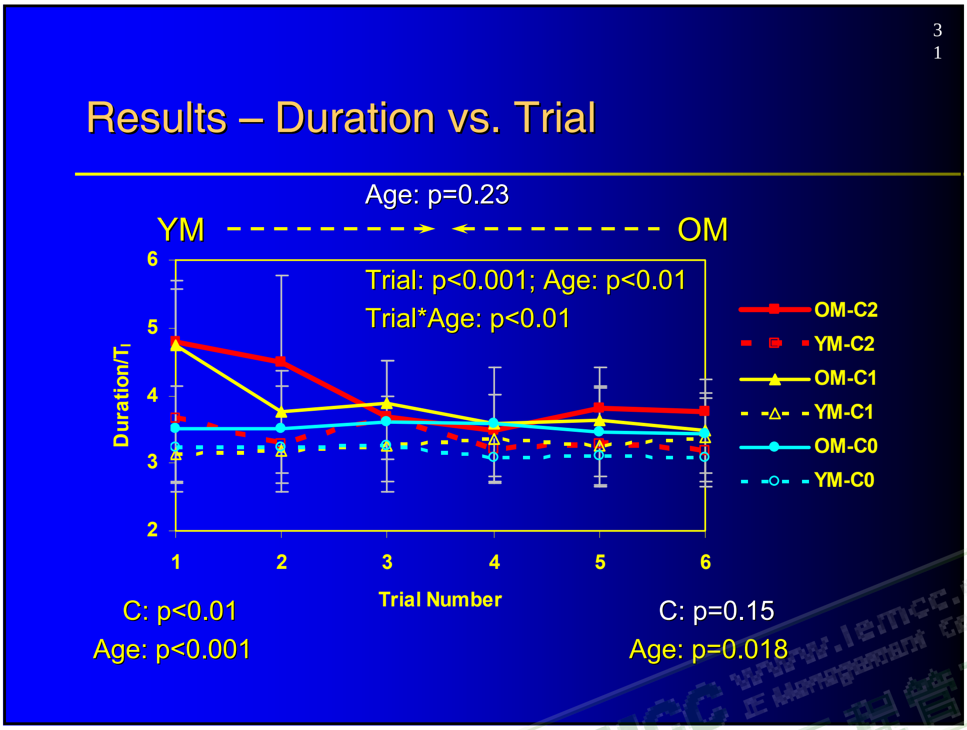


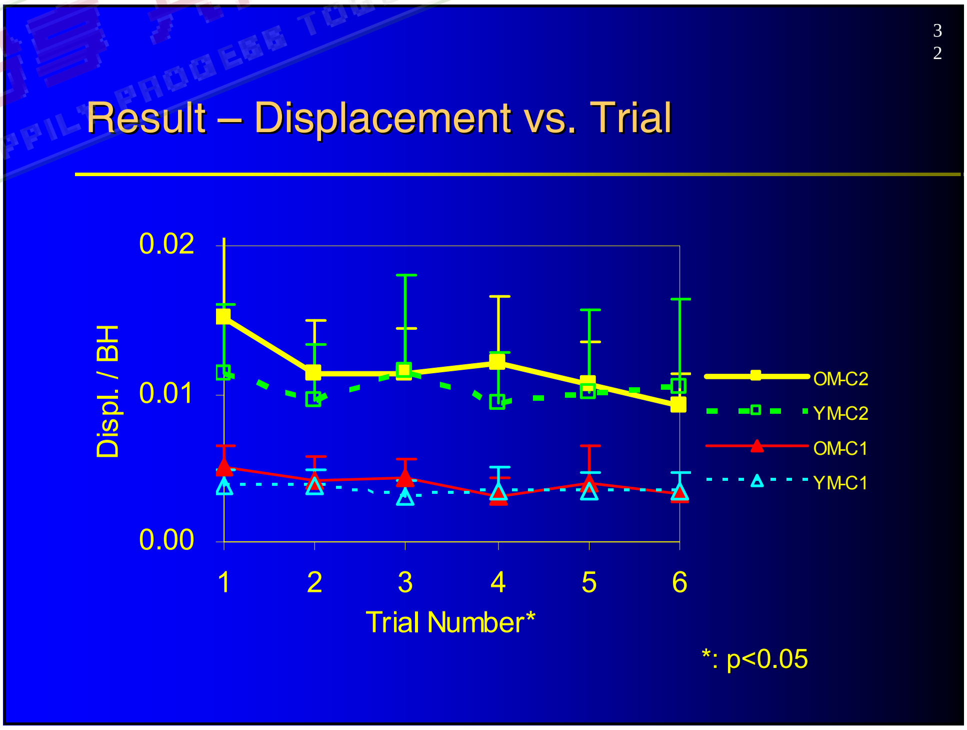
Results – Duration vs. Trial on C1



Results – Duration vs. Trial on C2




3
1
Results – Duration vs. Trial
Age: p=0.23
YM
OM
Trial: p<0.001; Age: p<0.01
Trial*Age: p<0.01
Duration/Ti
6
5
4
3
2
1
2
3
4
5
6
Trial Number
OM-C2
YM-C2
OM-C1
YM-C1
OM-C0
YM-C0
C: p<0.01
Age: p<0.001
C: p=0.15
Age: p=0.018


3
2
Result – Displacement vs. Trial
0.02
0.01
0.00
Displ. / BH
1
2
3
4
5
6
Trial Number*
OM-C2
YM-C2
OM-C1
YM-C1
*: p<0.05

33

Conclusions

- After 5 practice trials, structural compliance did not affect the total duration.
- YM could adapt to the structural compliance within the first stepping trial.
- OM might not be able to accurately control stepping movement in the first trial; however, they are able to adapt to structural compliance within 2-3 trials.
- OM are able to compensate for most age differences in stepping movements by practice.

34

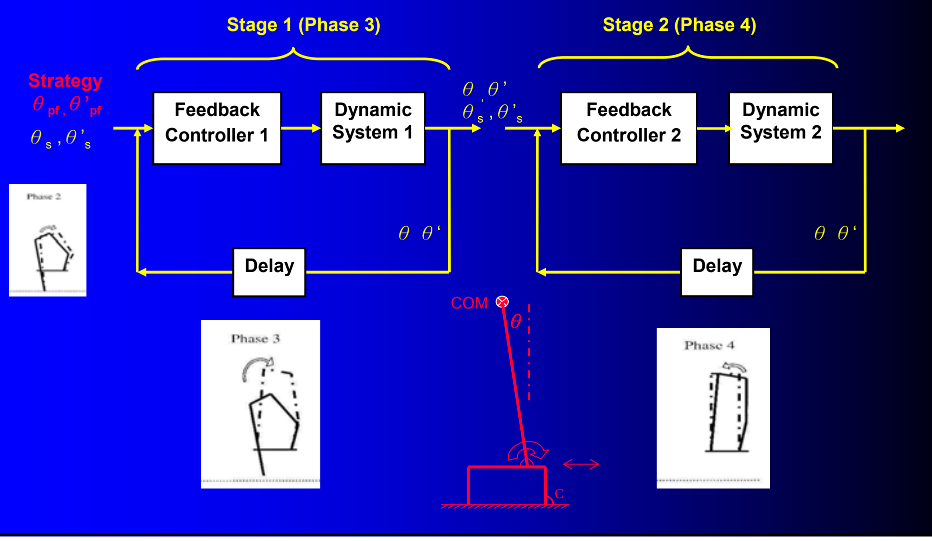
Research Outline

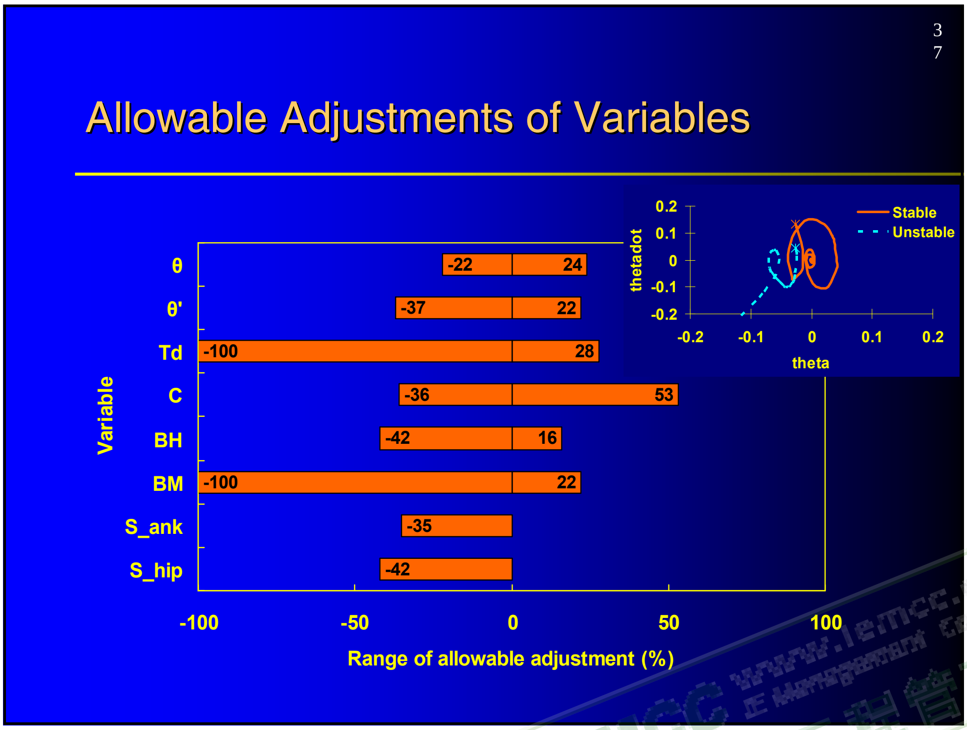
- Feasible lateral weight transfer on rigid structures
- Effects of unexpected structural compliance on stepping and balancing behavior
- Adaptive changes of stepping movements
- Effects of stepping strategy on system stability

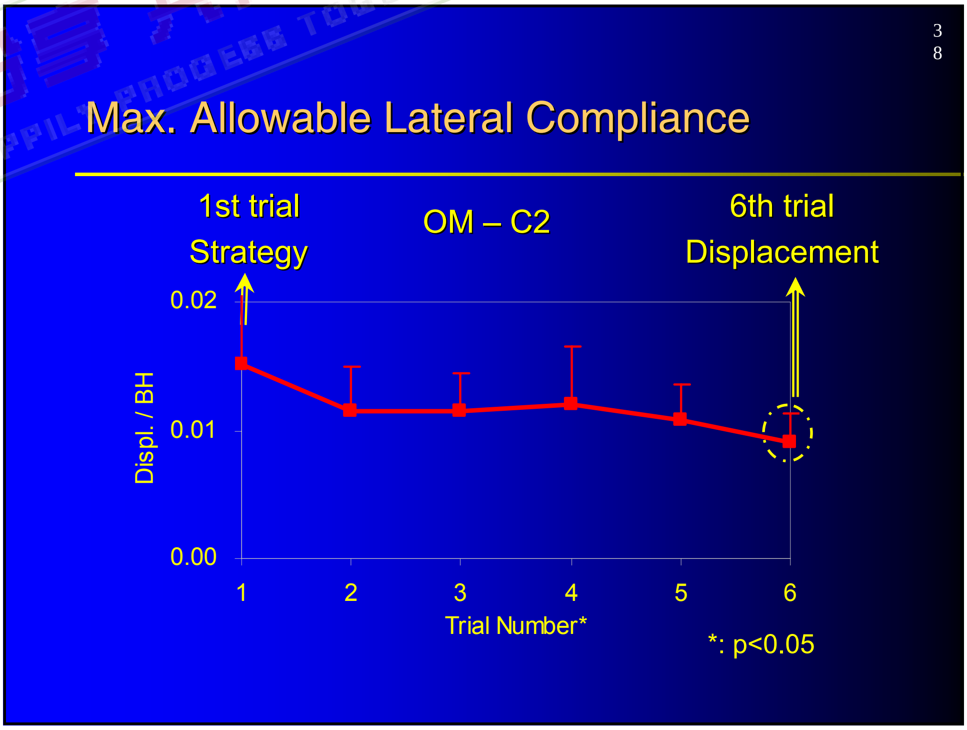
Hypotheses

- Primary null hypothesis
  - Stepping strategy does not affect the lateral stability of the human-compliant structure system.
- Secondary null hypothesis
  - System parameters do not affect the system stability.

Biomechanical Model

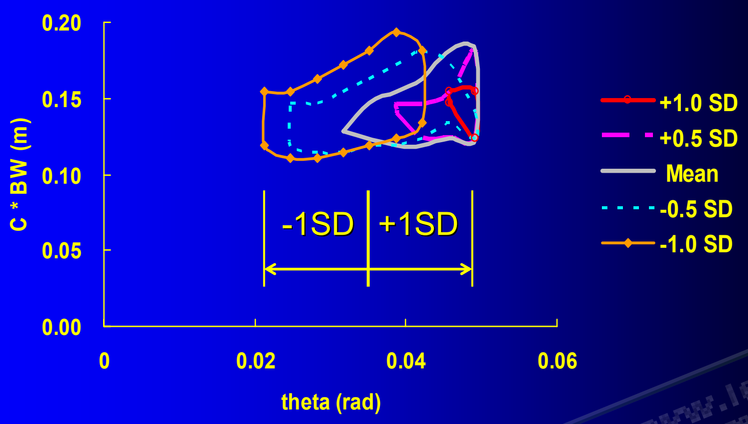



37
Allowable Adjustments of Variables
Variable
θ
θ'
Td
C
BH
BM
S_ank
S_hip
-22
24
-37
22
-100
28
-36
53
-42
16
-100
22
-35
-42
-100
-50
0
50
100
Range of allowable adjustment (%)
thetadot
theta
Stable
Unstable
0.2
0.1
0
-0.1
-0.2
-0.2
-0.1
0
0.1
0.2


38
Max. Allowable Lateral Compliance
1st trial
Strategy
OM – C2
6th trial
Displacement
Displ. / BH
0.02
0.01
0.00
1
2
3
4
5
6
Trial Number*
*: p<0.05

39

Max. Allowable Lateral Compliance



40

Conclusions

- Stepping strategy can affect the system lateral stability.
- Lateral movement of system is most sensitive to the lateral COM velocity and displacement at the trail-foot push-off.
- Allowable maximum compliance based on our experiment should be less than 0.12 m/BW (in N).
- Obesity might reduce the maximum allowable structural compliance.

41

Research Questions

- What are the factors that affect lateral stability of a human standing on a rigid, non-fixed, raised structure?
- How does the lateral structural compliance affect subjects' stepping and balancing behavior?
- Are there any age or gender effects on such behavior?
- Are there any learning effects on balancing on a laterally-compliant raised structure?
- Can we improve the safety of such structures?

42

Concluding Remarks

- No Lift-off region is predicted.
- >10 degree "A"-shape angle should be used.
- Lateral tool force is limited on a raised structure.
- Lateral structural compliance and age significantly affect stepping and balancing behavior.
- Practice can eliminate the effect of structural compliance.
- Practice can compensate for age differences.
- Slow stepping/lateral movements are recommended.
- Lateral structural compliance should be less than 0.12m/BW.
- Obese people should use stiffer raised structures.

Acknowledgements

Dr. James A. Ashton-Miller
Janet Kemp
Adrian Figueroa
Martin Stenzel
Biomechanics Research Laboratory
University of Michigan

U.S. National Institute of Health
NIA-5-P01-AG10542
PHS P50 AG08808