WHITE PAPER:

Prediction of ground reaction forces and moments by using gait analysis silhouette tracking method compared to marker tracking and force platform method

Mischa Muehling[1],Tim Weber [1, 2], Philipp Russ[3], Sebastian Dendorfer [1, 2]

[1] Laboratory for Biomechanics, Ostbayerische Technische Hochschule Regensburg, Regensburg, Germany,

[2] Regensburg Center of Biomedical Engineering, OTH and University Regensburg, Regensburg, Germany

[3] Simi Reality Motion Systems GmbH, Unterschleißheim, Germany

***Abstract*—Marker based tracking and using force platforms is the common way to capture human motion and ground reaction forces, but it is not as time efficient as other new methods like silhouette-based tracking. This study investigates the differences between marker-based motion and silhouette-relying motion data based on predicting ground reaction forces with a musculoskeletal simulation model of one subject squatting on one leg. The subject was recorded using a motion capture system including eight 0.3 megapixel (MP) cameras with a sample frequency of 100 Hz. The ground reaction forces were measured by a force platform (Kistler, Ostfildern Germany) at 1000 Hz. The comparison between the gold standard (marker-based with force platforms) and the silhouette based approach shows resulting joint reaction force correlations between 0.84 and 0.99 with only one exception: the lateral moment of the knee (limb in contact) at 0.66 correlation. The predicted total force vector at the silhouette-based model showed a correlation coefficient of 0.95 to the gold standard. The promising results indicate that silhouette tracking is on the way to be an alternative to the common marker method in conjunction with force platforms.**

Keywords: Musculoskeletal model, Simi Shape, Silhouette tracking, Ground reaction force prediction

I. Introduction

Motion analyses is, among other applications, used to explore the forces and moments in the human body in order to calculate muscle forces, effects of muscle injury, forces in human joints, effects of medical treatments and more [2][3].

To acquire movement data several methods of recording humans are available.

Motion capture (MoCap) is commonly executed with retro-reflective markers, which are attached to the subjects and illuminated by infrared or visible light depending on the system. Often the subject recorded by several cameras and the analyses software calculates the three-dimensional locations of the markers out of the two-dimensional information of every camera. Affixing the markers onto the subject is a time consuming process. The marker-based method has some additional disadvantages like skin movement artifacts or noise on skin mounted marker data [1]. Due to the disadvantages of retro-reflective markers, silhouette tracking yields the possibility to become the gold standard. Thus, this investigation compares the silhouette-based tracking system with the marker-based tracking system of Simi (Simi Reality Motion Systems GmbH, Unterschleißheim, Germany).

II. Material and Methods

A. Instrumentation

The data was acquired by an optical motion capture system (Simi System, Unterschleißheim, Germany) using eight 0.3 megapixels (MP) cameras sampled at 100 Hz. 45 retro-reflective markers were placed on the subject (Fig. 1), according to the Simi Motion Inverse Kinematic model and 4 additional on the edges of the force platform. In order to measure ground reaction forces a Kistler force platform (Type 9286A) was used, sampling at 1000 Hz. The force platform was measuring eight channels: two medio-lateral, two antero-posterior and four proximo-distal channels.

B. Experimental setup

One healthy male subject (age: 25, height: 175 cm, weight: 72 kg) was recorded performing five one-legged squats wearing retro-reflective markers. To achieve optimal settings for silhouette tracking a minimum set of garment was chosen. The movement was done on the Kistler force platform on the left leg with a required maximum knee flexion of 60°. The acquisition was executed at the Simi Reality Motion Systems lab.

Corresponding author: Sebastian Dendorfer,
Regensburg Center of Biomedical Engineering,
am Biopark 9, 93053 Regensburg, www.lbm.rcbe.de

Tel: +499419435171
Fax: +499419439699

Mail: sebastian.dendorfer@oth-regensburg.de

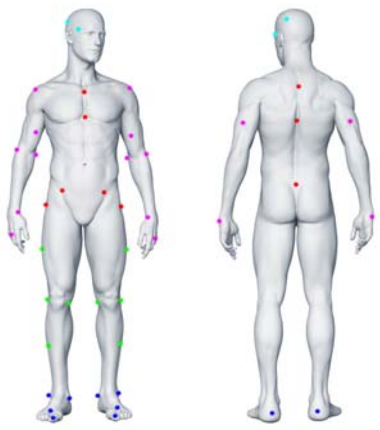

Figure 1: Simi inverse dynamics marker setup

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C. Acquiring 3D Data

The 3D data was created on the one hand by the Simi Motion software (Version 9.1.0) for marker trajectories and on the other hand by the Simi Shape (Version 2.1.0) software based on the same video input. Simi Motion software is using retro-reflective markers which are illuminated by LED lights forcing the markers to reflect in bright white. The user defines the initial position of the markers in at least two acquisitions to locate them two-dimensional. Simi Motion calculates the three-dimensional location of the markers based on the two-dimensional information of the acquisitions and the location of the cameras. The Shape program uses background subtraction techniques to track the silhouette of moving objects in the video, without using markers. A human model is superimposed on to the silhouette of the two-dimensional acquisitions. This allows the calculation subject's joint centers based on the 2D information. The overlay model has to be scaled, which was done manually in this case.

The kinematic model was iteratively (five times) adjusted to the 2D silhouette in order to reduce the overall kinematic error.

D. Musculoskeletal Simulation

The AnyBody Modeling System™ (AMS - AnyBody Technology, Aalborg – Version 6.0.4.4327 (64-bit)) was used to analyze the forces and moments regarding the human body [4]. The 3D marker trajectories were setting up the motion capture full body model (MoCap-Model) of the AnyBody Managed Repository (Version 1.6.2). While the Simi Motion data can be used in the standard MoCap-Model with adjusted markers, the Simi Shape data has not enough information in shape of joint centers (pseudo markers) to set up a good fitting movement of the standard MoCap-Model, so the degrees of freedom (DOFs) in the MoCap-Model for the silhouette data were adjusted:

- Ankle subtalar eversion DOF set to 0.23°
- Elbow pronation DOF set to 30°
- Wrist flexion and abduction DOF set to 0°

This results in 2x4 DOFs (right and left leg) which were fixed in comparison to the original MoCap AnyBody model.
Overall 4 AnyBody models - 2 for each silhouette and marker data once with the ground reaction force prediction module (GRFP) and the other one with the measured forces of the force platform - were created.

The standard optimization routines of AnyBody were used to optimize segment lengths of thighs, shanks, upper- and lower arms.

E. Data processing

The subject performed five squats, but only three of them were analyzed, due to the fact that the AnyBody models went unstable during squat one and five. The following data is relying to squat two to four, resulting in a total of three one-legged squats.
Since marker tracking and acquiring force plate data is the common state of the art in the biomechanical sector the following data is compared to this.

Differences and correlation between the following AMS models were conducted: marker model and shape model with GRFP; model based on the silhouette and force plate data and the model based on marker and force plate data.

The total force vectors normalized to the bodyweight of the different processing types are compared. A correlation analyses was done between the marker force plate model and the other models to show differences between the data. Additionally, the root-mean-square deviation (RMSD) was calculated to discover the deviation of the predicted to the measured data.

The silhouette based movement data (knee flexion and hip flexion) was smoothed by moving average with a span of 20 frames to show of a trend of the curves and delete outliers.

III. Results

A. General

In a first step, knee and hip flexion as computed by the AMS are compared. The knee flexions show a correlation of about 0.95 either for the left and right knee (Fig. 2 and Fig. 3). The hip flexion of the left leg shows an offset between 10 to 30 degrees (Fig. 4).

The amount of the total force vector of the force plate and GRFP module is almost matching. Only some peaks of the silhouette GRFP at the extension of the knee are conspicuous due to differences of about 0.5 times bodyweight to the other total reaction forces (Fig. 6). The antero-posterior and the medio-lateral ground reaction forces are negligible in this context (Tab. 3.1).

The correlation coefficients of the total ground reaction forces and the proximo distal ground reaction force are between 0.95 and 0.99 at both GRFP models (Tab 3.2). Additionally, the silhouette data RMSD is almost twice of magnitude compared to the marker based data (Tab 3.3). The highest value of RMSD of the ground reaction forces is 0.04 at the proximo distal ground reaction force of the silhouette based data (Tab 3.3).

The correlations of the forces of the left leg are consistently in a range between 0.84 and 1.00, with the exception of the lateral moment of the silhouette based model, which has a value of 0.66 (Tab. 3.4).

The RMSD of the forces in the claimed leg are fairly different between the different models. While the maximum value in the marker based GRFP model is the proximo distal force of the knee at 0.58, the max force in the silhouette based GRFP model is the proximo distal force of the Ankle at 1.53 times bodyweight (Tab. 3.5).

B. Figures

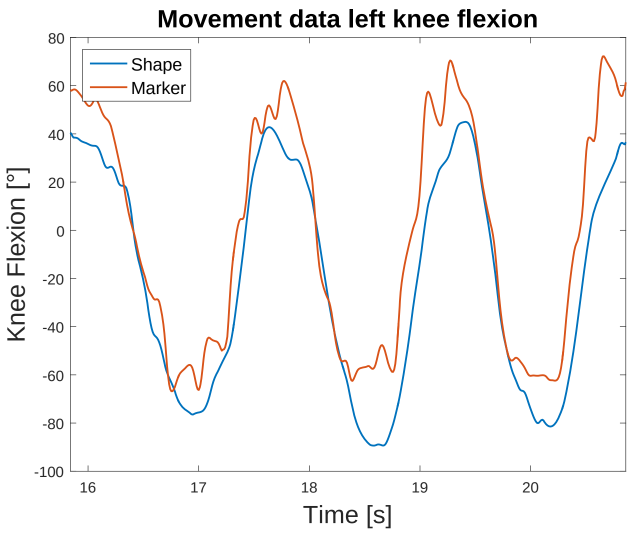

Figure 2: Knee flexion of the left knee of nonsmoothed marker data and smoothed silhouette data

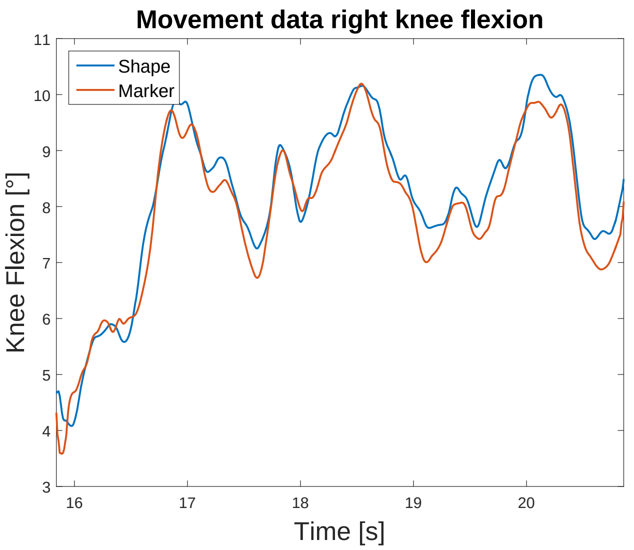

Figure 3: Knee flexion of the left knee of nonsmoothed marker data and smoothed silhouette data

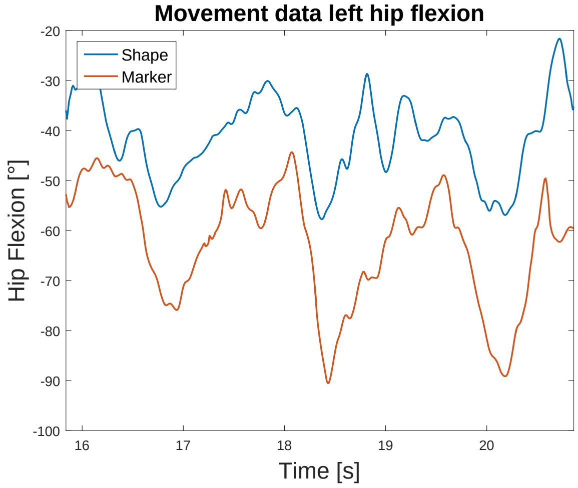

Figure 4: Hip flexion of the left leg nonsmoothed marker data and smoothed silhouette data

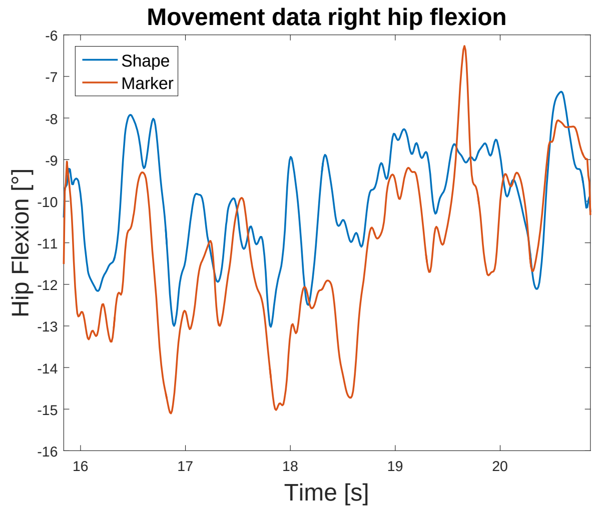

Figure 5: Hip flexion of the right leg nonsmoothed marker data and smoothed silhouette data

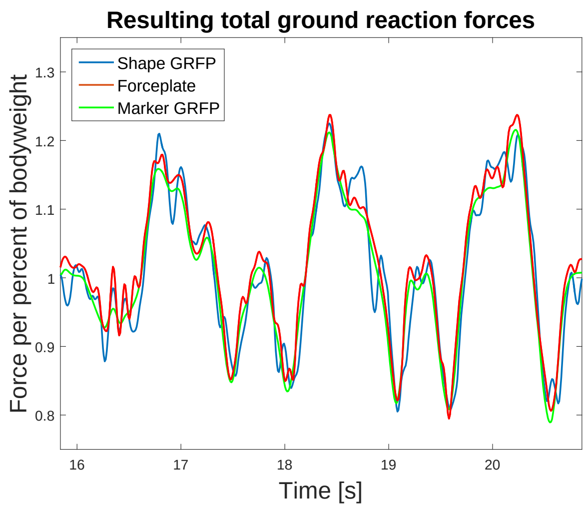

Figure 6: Total force vectors of measured and predicted force

C. Tables

TABLE 3.1
MAXIMUM FORCES OF COMPONENTS OF THE GROUND REACTION FORCE

Force plate	GRFP Marker	GRFP Shape	Force plate
Proximo distal force	858.5 N	865.1 N	873.7 N
Antero posterior force	40.7 N	67.0 N	33.2 N
Medio lateral force	30.6 N	32.7 N	6.5 N

TABLE 3.2
CORRELATION TO THE MARKER BASED FORCE PLATE DATA

Force plate	GRFP Marker	GRFP Shape	Force plate Shape
Total force	0.99	0.95	1
Proximo distal Force	0.99	0.95	1

TABLE 3.3
RMSD TO THE MARKER BASED FORCE PLATE DATA NORMALIZED TO THE BODYWEIGHT

Force plate	GRFP Marker	GRFP Shape	Force plate Shape
Total force	0.02	0.04	0
Proximo distal Force	0.02	0.04	0

TABLE 3.4
CORRELATION OF JOINT REACTION FORCES TO THE MARKER BASED FORCE PLATE MODEL

Location	GRFP Marker	GRFP Shape	Force plate Shape
Antero posterior force Correlation			
Ankle	0.99	0.97	0.98
Knee	1.00	0.99	0.99
Hip	0.99	0.96	0.99
Medio lateral force Correlation			
Ankle	0.99	0.94	0.99
Knee	1.00	0.99	0.99
Hip	0.98	0.92	0.99
Proximo distal force Correlation			
Ankle	0.99	0.92	0.99
Knee	0.94	0.84	0.97
Hip	0.97	0.89	0.99
Axial moment Correlation			
Ankle	0.99	0.93	0.98
Knee	0.99	0.98	0.99
Lateral moment Correlation			
Knee	0.91	0.66	0.86

TABLE 3.5
RMSD OF THE JOINT REACTION FORCES TO THE MARKER BASED FORCE PLATE MODEL NORMALIZED TO THE BODYWEIGHT

Location	GRFP Marker	GRFP Shape	Force plate Shape
Antero posterior force RMSD			
Ankle	0.16	0.30	0.31
Knee	0.17	0.46	0.64
Hip	0.06	0.13	0.06
Medio lateral force RMSD			
Ankle	0.09	0.35	0.19
Knee	0.17	0.46	0.64
Hip	0.37	0.30	0.21
Proximo distal force RMSD			
Ankle	0.41	1.53	0.43
Knee	0.58	0.87	0.35
Hip	0.56	0.41	0.14
Axial moment RMSD [Nm/kg]			
Ankle	0.04	0.09	0.07
Knee	0.05	0.09	0.13
Lateral moment RMSD [Nm/kg]			
Knee	0.20	0.14	0.10

IV. DISCUSSION

In general, the silhouette-based ground reaction force prediction model fits well with the force plate models.

The total ground reaction force of the shape GRFP model shows some peaks of ground reaction force. As already mentioned, the motion of the shape GRFP model is driven by only 17 markers (the joint centers), due to the fact that the model was only driven by jointer centers and required markers at the middle of the hand and the head segments to define it. Therefore motion will differ from the motion of the marker-based model, because the marker model is driven by 47 markers. Nevertheless, the correlation is at 0.95 which is still fairly high. Additionally, the kinematics of the Ankle and therefore the foot kinematics are differing from the marker based motion data which is recognizable at the RMSD of the proximo distal force of the Ankle at 1.53 (Tab. 3.5). This value is at least 3 times as high as in the other models. The correlation of the proximo distal force in the ankle is 7 points lower than in the other models as well, which are at 0.99 correlation (Tab. 3.4).

The low correlation of the lateral moment of the knee at 0.66 is caused by the fact that the subtalar eversion of the Ankle was set to a fix level. This caused a higher amount of moment in the knee (Tab. 3.4).

The differences in hip flexion can be explained by the fact that the silhouette-based data has only one marker to define the pelvis in AnyBody. Usually there were used four markers to define the precise position in 3D for a pelvis. Due to that and the kinematic chain, the pelvis has large changes in rotation when a single pseudo marker moves. So the upper body rotates and therefore the hip flexion changes. Additionally, the knee flexion and position is deviating slightly in some steps - especially at the extremes the curves differ - which has an effect onto the hip flexion as well, because the knee flexion defines the position of the thigh. This can be seen in figure 2, where the highest offset from marker to silhouette-based data is at the maximum flexion of the left knee. By using available hybrid methods of marker based tracking and silhouette tracking, these limitations can be overcome and this error can be minimized. In the course of this work the full range of marker based methods and silhouette based methods has been explored, the influence of hybrid methods is a focus for further research.

The correlation of the GRFP shape model between the force plate data is smaller compared to the GRFP marker model and the force plate data. This indicates that the GRFP marker model is more precise in term of ground reaction force prediction, mainly due to the fact that the GRFP marker model is driven by 47 markers instead of 17 markers in the GRFP shape model. In most cases the force plate shape model shows a lower correlation than the GRFP marker model as well, which proves this hypothesis (Tab 3.4).

Some errors may be introduced at the shape overlay model setup for tracking. In the used model the segment lengths were adjusted manually. This resulted in some differences between the shape and the marker model, regarding the arm segment lengths and the leg segment lengths. The legs had to be oversized by a minimum so the overlay model does not shake, while the iteration of position in every frame. This results in slightly different joint centers especially in the knee joint (Fig. 8). Results may improve when the shape overlay model is more precise to the silhouette of the subject. The Silhouette model can of course be improved by using a background which is rich in contrast, yet this is the case for all MoCap tracking methods which rely on background subtraction. The reader should note that this is improved in a subsequent software version of Simi Motion, which was not available at that time.

In the case of this investigation the average smooth over 20 frames was well fitting. It is not sure that this is working on other data as well, because the measurement was only done for one subject with one movement. So the filter is not ensured to be the perfect solution for every measurement. The effect is shown on figure 7: the smooth of the left knee flexion.

The correlation could be better if the joint velocities and accelerations would be used to drive the prediction model, but in case of comparability the pseudo markers are the better choice, because the marker based force plate model is driven by markers as well. So the comparison can be done without worrying about different model types.

The standard MoCap model of the AnyBody Repository was used as template to set up the musculoskeletal models for the analysis. The changes of the DOFs of the model could have changed the calculation of the forces and moments. The subject was performing the squats on the left leg only, which means that it had to keep the balance. Due to that it had to use the subtalar eversion of the left ankle to achieve that.

Marker tracking is state of the art in cases of recording human movement data. Nevertheless, it has its weaknesses which are once a maximum error without a human interaction of 1.5% [1], second the error in marker placement caused by humans [1] and third the soft tissue displacement of human skin [5]. So the comparison of the silhouette based data to the marker based data includes the errors of the marker tracking.

The anatomy of the human body is simplified in the used AnyBody MoCap model. Particularly the complexity of muscle anatomy concerning the muscle recruitment and strength. The joint anatomy concerning the degrees of freedom is reduced, for example the knee joint is only able to perform flexion.

The bones in the AnyBody models are rigid bodies so they are not elastic or plastic deformable.

The model was using the principle of inverse dynamics which excludes the possibility of direct force dependent joint displacements.

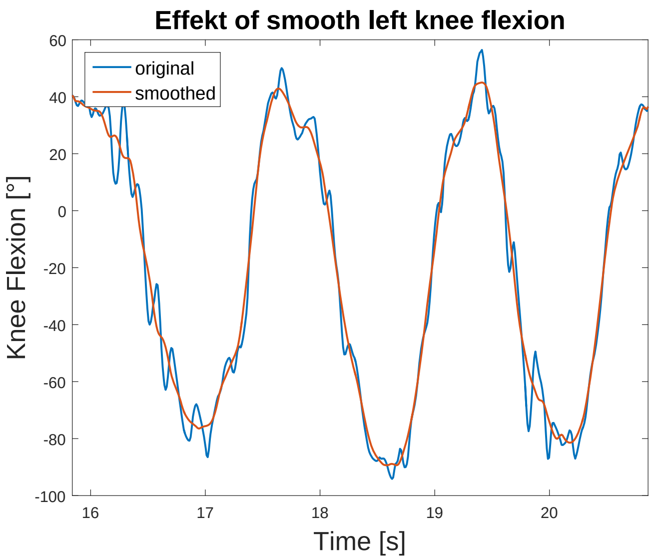

Figure 7: Smoothing effect at a span of 20 frames over silhouette-based data

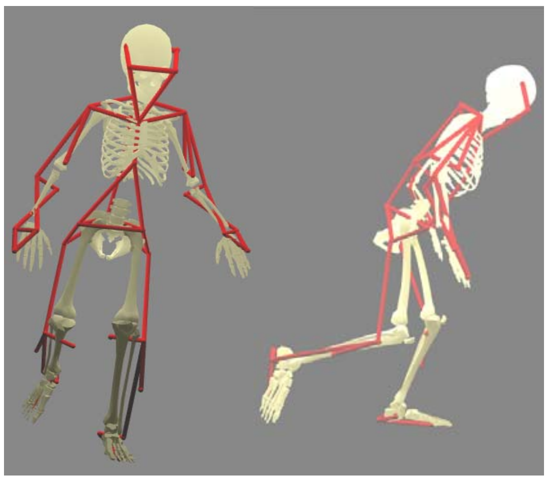

Figure 8: Comparison of movement data silhouette (skeleton) vs. marker (lines)

V. CONCLUSION

All in all, the silhouette based data fits well to the marker based force plate calculation in this investigation. The difference in correlation in most results are at a minimum, the silhouette tracked data is still between 0.84 and 0.99. The RMSD of the silhouette data to the gold standard lies between 0.13 and 1.53. The correlation of the total force vectors of 0. 95 shows, that the prediction module is working well with the silhouette based data. A challenge with the definition of the pelvis segment occurred, because the silhouette based data only provides one pseudo marker to define the pelvis, yet hybrid methods exist which could, depending on the analysis, counteract this effect, therefore minimizing large differences of the pelvis rotation compared to the gold standard.

VI. FUTURE WORK

In future, the silhouette data should be driven by the measured joint angle velocities and accelerations to avoid the problem of too less markers. This would decline most of the problems and make the AnyBody model more flexible for different subjects measured, because the dimensions of the subject would have an impact on the pseudo markers in the AnyBody model.

The silhouette tracking system should be more precise and the setup of the overlay model should be automated in future versions of the software, so the possibility of human errors and the time of data processing should be reduced by a large amount.

Especially for the use in studies with high subject quantities, a silhouette tracking system is more efficient, because the time consuming process of marker placement is not necessary anymore and the difference in motion data is not significant except for the pelvis rotation.

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