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Original Article

Effect of high heel gait on hip and knee-ankle-foot rollover characteristics while walking over inclined surfaces — A pilot study

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ABSTRACT

Given the massive number of individuals wearing high-heeled shoes, understanding the gait biomechanics associated with their use could provide insight into clinically preventable abnormalities. The effects of inclined surfaces on the high-heeled gait have been investigated in the present pilot study, as most walking surfaces encountered in routine life are rarely perfectly level grounded. The rollover shapes of the high-heel shod gait are calculated to obtain the desired results. An adjustable inclined walkway setup was fabricated and comprising fixed slots permitting discrete and variable angle of inclinations ($\leq 30°$). The gait trials were recorded for the heel shod walking of ten healthy female volunteers using the three-dimensional motion analysis system by varying the inclination of the fabricated walkway. From the calculated rollover shapes, the necessary radii of the hip and the knee-ankle- foot rollover shapes were obtained and a repeated measures analysis of variance was carried out to establish the existence of correlation between the angle of inclination and rollover radii. The results of the present pilot study show that for high heel-shod walking there exist variable radii of curvature for early and late stance phases and that the same may vary depending upon the inclination. The same information can be used to modify the design of high-heel shoes to improve the stability while retaining their aesthetics.

1. Introduction

The use of high heeled shoes leads to an apparent increase in height, augments confidence and provides an aesthetic look, more so to women, as reported by Linder and Saltzman [1]. However, several articles report the detrimental effects of high-heeled shoes on the body posture and foot health when worn regularly over an extended period [1,2]. Previous research on the high-heeled gait has deduced that regular use of high heels is unhealthy and can lead to osteoarthritis, back pains and other gait abnormalities [3]. In general, the female population wears heels regularly (ranging from low height heels to stiletto heels), and this is one of the cause of chronic pain in the lower spine due to the additional compressive forces acting on the lumbar spine and can lead to chronic discomfort [4]. More recently, with the use of 3D motion analysis systems the human gait and its associated kinesiology during high heel shod walking has been reported, and this investigation has concluded that the regular users of high-heeled shoes have a lower mediolateral stability as compared to infrequent users [5]. Esenyel et al. have carried out a comparative study of gait patterns from flat and high heeled shoes and have observed that the walking speed and the vertical ground reaction forces decrease significantly in case of walking with high heeled shoes [2]. The electromyography (EMG) study of the high heeled gait reports that the EMG activity is higher in the muscle groups that lead to eversion of the heel [6].

The effective translation of the foot about the hip, knee and ankle joints generates a curved shape, i.e. the rollover shape, corresponding to the stance phase of the gait cycle. These rollover shapes have been determined and analysed for the knee-ankle-foot (KAF) and hip-ankle foot systems, in multiple studies by Curtze et al. and Hansen et al., to investigate the effects of healthy limbs, prosthetics, shoes (including high-heels) on level ground walking [7–15]. In a related study it has been concluded by Hansen and Childress that the rollover shapes for healthy participants do not change significantly upon changing the shoe heel heights as the ankle-foot systems adapt to the varying conditions [16]. Thus, with changes in the walking conditions, the rollover shapes are invariant, whereas the kinetic and kinematic gait parameters present a change, thereby suggesting that the variance in the rollover shapes may indicate altered stability and comfort. In addition, there have been studies that predict the rollover shapes of the human foot by using predictive analytical models [17–19]. The prospects of high heel shoes in rehabilitation have also been considered in a study by Meier et al. that

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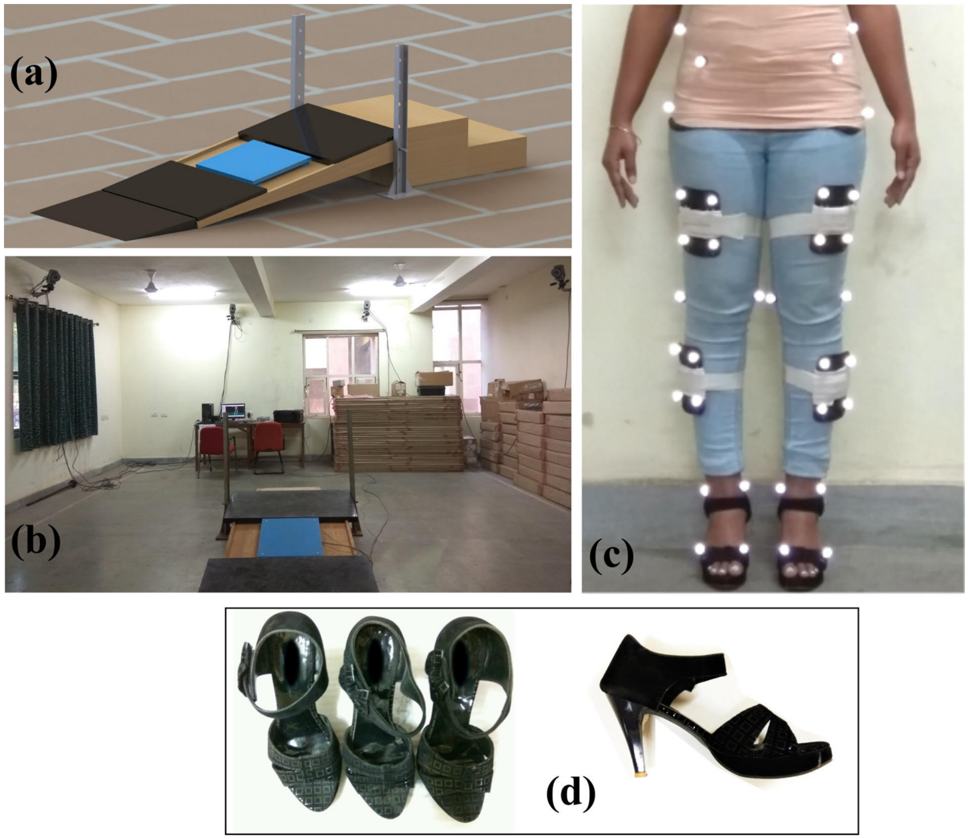

Fig. 1. (a) The CAD representation of the adjustable inclined walkway, (b) the experimental setup (c) the retro-reflective marker setup, and (d) the high-heeled shoes used in this study.

discusses the development of inexpensive prosthetic feet for high-heel shoes for the desirous users [20].

In general, the construction standards of ramps in buildings such as hospitals, retiree homes, public buildings as well as housing areas dictate a slope of 1:12 for design purposes [21]. These slopes may be increased up to 1:10 owing to space limitations [22]. Apart from these surfaces, most of the walking surfaces encountered in daily life are rarely perfectly level and have at least some level of inclination, and most research to date have not taken this factor into account. Further, the effect of inclination on the rollover shapes of the high-heeled gait has not been reported yet. Hence, the present pilot study considers the effects of high-heel shod walking over the inclined surfaces on the stability of the joints as these could be detrimental to the lower limb health. This pilot study is conducted to evaluate the stability provided by high-heel-shod gait during ascent on inclined surfaces, from a perspective of the rollover shapes. The effects are studied by recording the joint translational data as well as the centre of pressure during the stance phase of the gait cycle. The rollover shapes for each inclination is determined, and qualitative analysis is performed using curve-fitting and statistical methods.

2. Material and methods

2.1. Selection of volunteers

Ten healthy female volunteers aged between 20–27 years having body weight and height within ranges of 51.8 ± 4.35 kg and 1.58 ± 0.056 m were selected for the gait trials. The participants had no anatomical deformities and were regular wearers of high heeled shoes. This study was approved by the Institutional Ethics Committee with the relevant order No. NITRKL/IEC/FORM-2/23-11-2015/19. Before conducting the trials, all the participants were informed about the details of the gait trials and written consent was obtained from them.

2.2. The experimental setup

The gait trials for this research were recorded using a four camera motion capture system provided by Qualisys (Oqus 5.0) and a KISTLER (9260AA6) force platform, which was integrated into the walkway. For the recording of data, a computer data acquisition system was connected synchronously to the four camera motion capture system and the force platform. Now, the gait trials were conducted using the fabricated walkway and the necessary motion including the associated data recorded via Qualisys Track Manager and Visual 3D (v5) post-processing software. The experimental setup for the trials on level ground consisted of a 6 m long walkway with the force plate integrated into it (at mid-length). For the trials on the inclined surface, an adjustable inclined walkway was fabricated in such a manner that it allowed discrete inclination angles within the range of 3°–30° as shown in Fig. 1(a–b). The first adjustment provided an angle of 3° while the remaining slots facilitated angles of different inclinations i.e., 10°, 15°, 20°, 25° and 30°. However, practice trials with participants wearing high-heels showed that none of the participants could walk at inclinations higher than the 15° without slipping, hence, all the trials were performed ≤15°. Additionally, a secondary supporting fixture was provided beneath the wooden platform, to maintain the allowable deflection i.e., < 1 mm during the gait-trials. Further, the wooden steps were placed at the end of the walkway to allow the volunteers to exit comfortably from the walkway.

2.3. Gait analysis

The high-heel shoes (3-in. heel height) were procured in three different foot sizes having a similar design to ensure a comfortable fit for maximum range of participants (Fig. 1(d)). A lower body retro reflective marker setup was used for the participants using the palpation method. The segments and joints of the participants were identified using 34 retro-

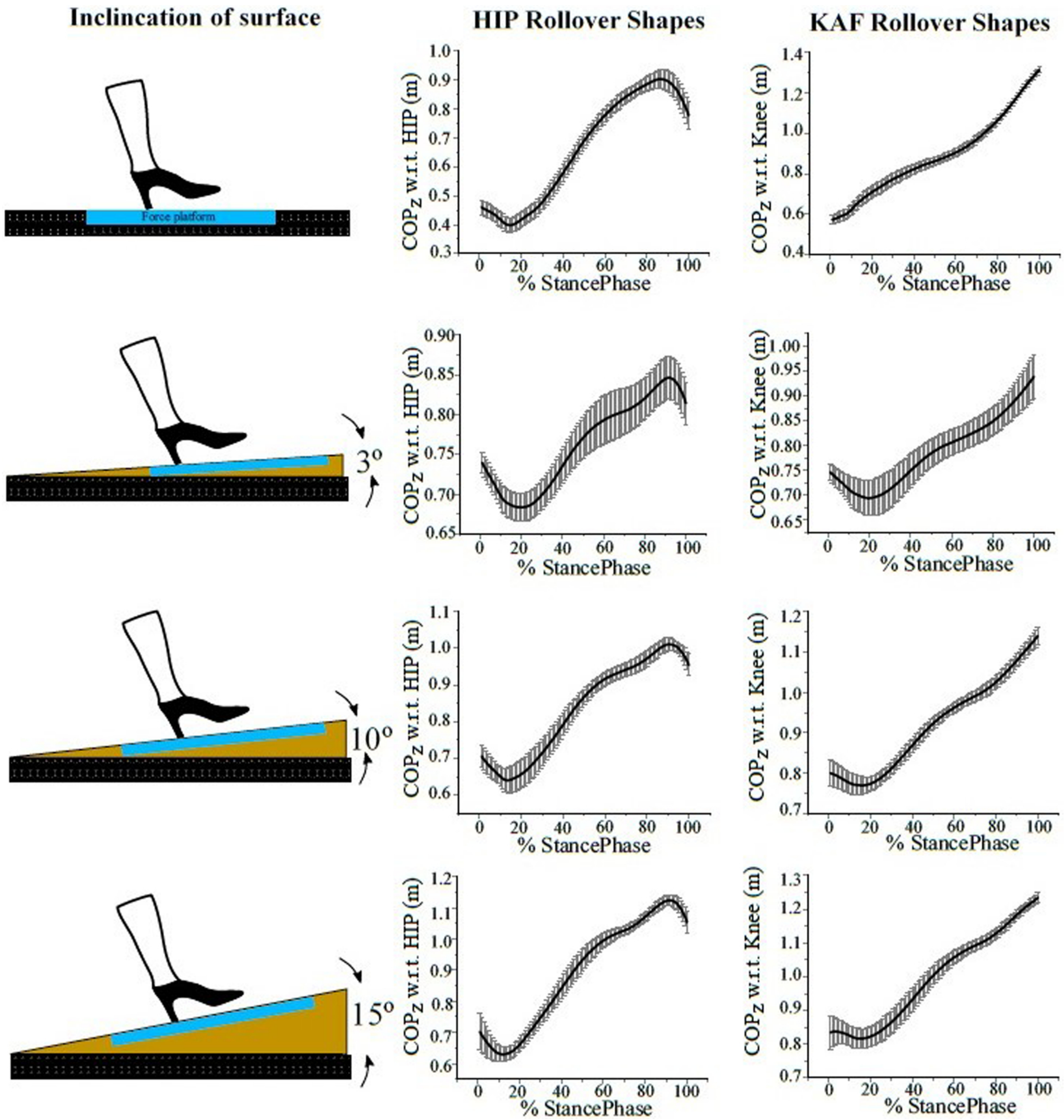

Fig. 2. The mean and standard deviations of the Hip and KAF rollover shapes for high-heeled gait on varying inclinations.

reflective markers, for 3-D gait analysis (Fig. 1(c)). The participants were asked to perform repeated practice trials with the high heeled shoes to get acquainted with it and to reduce the possibility of conscious gait. The participants walked the length of the walkway, upon an auditory cue, wearing the high heeled shoes and data acquisition was done. A total of 24 randomized trials were recorded for each participant, comprising six trials each for level ground, 1st level of inclination (0 slot), 2nd level of inclination (1st slot), and 3rd level of inclination (2nd slot) respectively. The higher levels of inclinations were excluded from the trials as the slope of the walkway proved to be too steep for participants.

2.4. Rollover shapes

The effective rollover shape was determined for each of the gait trials performed on the level ground, 0th slot, 1st slot and 2nd slot inclination of the inclined walkway by translating the vertical component of the centre of pressure (COP) coordinates with respect to the local coordinate system of the hip and knee joints. The resultant curves were the hip and knee-ankle-foot rollover shapes respectively. The rollover shapes corresponding to the early stance (ES) and late stance (LS) phases show visibly different curvatures. Hence, the results were exported to Origin Pro 2016 to perform circular curve fitting for ES and LS curvatures. The radii of curvature of each such fit was recorded for performing the statistical analysis.

2.5. Statistical analysis

The statistical analysis was carried out with the assumption that there is no inherent effect of gait asymmetry, between the leading and trailing limbs, on the parameters obtained. The radii of curvature of were tabulated, and were exported to MATLAB R2014b for statistical analysis. A repeated measures analysis of variance (RANOVA) was carried out corresponding to the radii of curvatures for each curve of ES and LS phases of the gait cycle. Further, the p-significance was calculated using Greenhouse-Geisser, Huynh-Feldt, and Lower bound corrections and the sphericity of the solution was checked using Mauchly method and epsilon correction method.

3. Results

The average rollover shapes (with respect to the hip and knee joint coordinate systems) obtained from a participant for gait trials on level ground, 0th slot, 1st slot and 2nd slot inclination of the inclined walkway

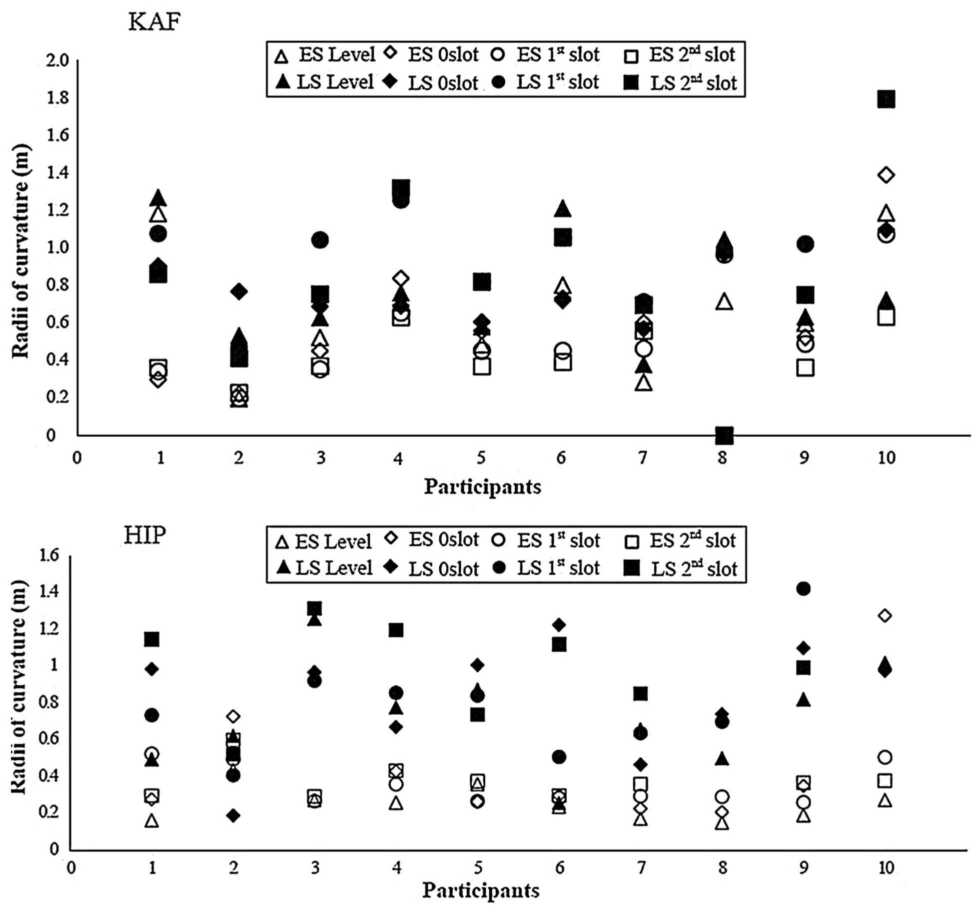

Fig. 3. The distribution of the radii of curvatures obtained for ES and LS phases of gait over level ground and varying inclinations of the ramp.

Table 1
The RANOVA results obtained for the radii corresponding to the Hip and KAF rollover shapes of all participants at LG and 1st, 2nd and 3rd inclinations of ramp.

	SumSq	DF	MeanSq	F	p-Value	p-GG	p-HF	p-LB
Hip shape radii								
Intercept	2.07×10^9	7	2.95×10^8	2.47	0.0178	0.0469	0.0402	0.1236
Participant	8.32×10^9	56	1.48×10^8	1.24	0.1328	0.1934	0.1818	0.3005
KAF shape radii								
Intercept	8.84×10^8	7	1.26×10^5	1.42	0.198	0.2347	0.2306	0.2406
Participant	5.74×10^9	56	1.03×10^8	1.15	0.2309	0.2879	0.2802	0.3512

Table 2
The results of mauchly's sphericity test and epsilon correction factors.

	Mauchly's sphericity test					Epsilon correction		
	W	ChiStat	DF	p-Value	Uncorrected	GG	HF	LB
Hip shape radii	0.09277	93.803	27	2.6×10^{-9}	1	0.56916	0.63626	0.14286
KAF shape radii	0.00128	262.78	27	1.7×10^{-40}	1	0.51642	0.57106	0.14286

are presented in Fig. 2. The mean and standard deviation of the curves are denoted by the thick solid line and the vertically shaded regions respectively. The radii of curvature for Hip and KAF shapes obtained corresponding to each participant for the ES and LS phases are presented in Fig. 3. The hollow and solid markers represent the ES and LS phase radii for the level ground and varying inclinations respectively.

The results obtained from the RANOVA for hip rollover radii and knee-ankle-foot (KAF) rollover radii are shown in Table 1. The values in the table present the degrees of freedom, the sum of squares, F-statistic, p-values, p-value (for the F-values), p-value with Greenhouse-Geisser adjustment, p-value with Huynh-Feldt adjustment, p-value with Lower bound adjustment and mean squared error. Furthermore, in Table 2 the results for Mauchly's sphericity test and epsilon correction factors for the p-values have been shown. The covariance between the radii of curvature values of the gait parameters early stance and late stance has been presented in the supplementary material. The positive and negative covariance between the parameters indicate the direct and inversely proportional relationships respectively.

4. Discussion

The mean rollover shape curves present an indication of the pattern of the curve for the high-heel shod gait analysis over level ground and ramped surfaces. These curves indicate that the shape has a non-uniform curvature over the duration of the entire stance phase. Specifically, there are two distinct regions of curvature that may be observed from the patterns. Hence, each pattern was segmented into two sub-regions and the radii of curvature for the ES and LS phases of each curvature were calculated. The values presented in Fig. 3, show a clear distinction between the radii of curvature obtained for ES (hollow markers) and LS (solid markers) phases. Further, most of the ES phase radii have a lower magnitude as compared to the LS phase values. Besides, the radii of curvature also increase with a rise in the inclination angle, as observed from Fig. 3. Thus, the phase of gait (ES or LS) as well as the inclination of the ramped walkway are instrumental in determining the effective curvature for a high-heel shod gait. A lower radius of curvature implies low stability for the loaded joint, which is true for the users of high heeled shoes, as the ES phase shows a distinctly lower radii of curvature. This occurs since the ankle is not able to provide sufficient plantarflexion to compensate the use of high heels [11]. It is due to this inability of the ankle to compensate for the high heels that the changes in rollover shapes are observed [11]. Thus it is possible that the ankle is more susceptible to injuries during the ES phase of the gait cycle.

The data obtained from the statistical analysis show the existence of interdependency between the shape parameter and the inclination angle of the ramp. The obtained high values (see Appendix Tables A1 and A2) of the covariance from the analysis corroborate the results. However, the F statistic value is 1.42 in the case of the KAF shape radii (Table 1) lies below the critical value of 2.18, thus making it unlikely for a relation to be established between inclination and radii of rollover shapes. The p-values corresponding to the F-statistic of the RANOVA for KAF shape radii data also present a low significance. Conversely, the F-statistic of the intercept for the Hip shape radii data presents a value of 2.47 (higher than the critical value), thus suggesting the existence of a relation between the radii and the angle of inclination. However, the F-statistic of the participants of the Hip shape radii presents a value lower than critical. Hence, this analysis may be indicative of the fact that angle of inclination of a ramp affects the rollover shapes of high-heel shod gait. Thus this study presents an exception where the rollover radii presents change with the conditions affecting gait, whereas previous studies have shown that the human body adjusts to the changes in the surrounding to maintain a constant radius of curvature [11]. As the radius of curvature is known to affect the ankle kinematics, the results of the present pilot study may have deep implications for the shoe industry. These results can be further quantified by conducting trials after incorporating design modifications to the stud/tip of the heel of these high-heel shoes. The stud end of the heel can be replaced with a stiff material having curvature corresponding to the rollover radii of the forefoot that might provide more anterior-posterior stability during rollover of the heel region in the ES phase. In a similar manner, the medio-lateral stability may also be improved by extending the base of the heel stud in the medio-lateral directions. As indicated by Hansen et al., the goal should be to provide design modifications that lead to an invariant rollover shape even as the conditions of walking change [11].

The present pilot study indicates that the design implications of the high-heel shoe soles and the stiffness of the shoe-sole layers may be crucial in determining the rollover shapes and the ankle stability. This pilot study presents certain limitations as only ten female participants have been considered and a single heel-height has been studied. However, the results present some interesting findings about the hip and knee-ankle-foot rollover characteristics, and the same could be investigated in a future study that overcomes these limitations.

5. Conclusion

The present study provides a critical overview regarding the rollover shapes of the high-heel shod gait for the healthy participants including the role of angle of inclination for the design of walkway and their end effects. In order to establish the inclination effect on the high-heel shod gait, an in-house ramp of variable inclination has been fabricated and utilized for the current experimental purpose. Subsequently, the recorded average rollover shapes and the obtained statistical data indicate substantial variation between the radius of curvature obtained for each ES and LS phase. The present findings may also help the users who intend to wear high-heel shoes with prosthetics as per the occupational demand. Interestingly, the current results may provide the foresight for the industry (shoe and prosthetic) personnel associated with design and their implementation to achieve the comfort for the end user.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A

Table A1
KAF rollover radii covariance.

	Level		0 slot		1st slot		2nd slot	
	ES	LS	ES	LS	ES	LS	ES	LS
ES	1.33×10^8	-6.22×10^6	9.69×10^6	851.72	−381.14	-1.67×10^7	−0.86	2.05×10^7
LS	-6.22×10^6	2.70×10^7	-4.19×10^6	−71.36	−182.79	1.13×10^7	−63.58	−39.71
ES	9.69×10^6	-4.19×10^6	-1.12×10^8	117.69	−416.29	-1.25×10^7	7.73	65.87
LS	851.72	−71.36	117.69	1.63×10^6	-1.66×10^6	2.30×10^6	−12.29	4.34×10^5
ES	−381.14	−182.79	−416.29	-1.66×10^6	2.46×10^8	-3.69×10^7	−135.62	-1.18×10^7
LS	-1.67×10^7	1.13×10^7	-1.25×10^7	2.30×10^6	-3.69×10^7	1.59×10^8	36.95	1.19×10^7
ES	−0.86	−63.58	7.73	−12.29	−135.62	36.95	0.0122	19.59
LS	2.05×10^7	−39.71	65.87	4.34×10^5	-1.18×10^7	1.19×10^7	19.59	2.52×10^7

Table A2
HIP rollover radii covariance.

	Level		0 slot		1st slot		2nd slot	
	ES	LS	ES	LS	ES	LS	ES	LS
ES	4.61×10^7	-2.17×10^3	-5.05×10^6	44.9	−73.16	6.95	2.89×10^7	554.55
LS	2.17×10^3	1.25×10^8	-7.53×10^6	-7.09×10^6	-1.08×10^7	-3.03×10^7	-2.23×10^7	1.20×10^7
ES	-5.05×10^6	-7.53×10^6	3.70×10^7	-1.60×10^6	119.66	1.13×10^6	-3.17×10^6	4.93×10^6
LS	44.9	-7.09×10^6	-1.60×10^6	4.86×10^7	-3.80×10^6	-1.97×10^7	-7.87×10^6	1.06×10^7
ES	−73.16	-1.08×10^7	119.66	-3.80×10^6	5.04×10^7	-2.59×10^7	2.26×10^7	-1.60×10^7
LS	6.95	-3.03×10^7	1.13×10^6	-1.97×10^7	-2.59×10^7	3.49×10^8	-5.19×10^6	-2.86×10^7
ES	2.89×10^7	-2.23×10^7	-3.17×10^6	-7.87×10^6	2.26×10^7	-5.19×10^6	1.08×10^8	-7.57×10^6
LS	554.55	1.20×10^7	4.93×10^6	1.06×10^7	-1.60×10^7	-2.86×10^7	-7.57×10^6	1.59×10^8

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