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# A test for normality based on the empirical distribution function

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**Abstract**

In this paper, a goodness-of-fit test for normality based on the comparison of the theoretical and empirical distributions is proposed. Critical values are obtained via Monte Carlo for several sample sizes and different significance levels. We study and compare the power of forty selected normality tests for a wide collection of alternative distributions. The new proposal is compared to some traditional test statistics, such as Kolmogorov-Smirnov, Kuiper, Cramér-von Mises, Anderson-Darling, Pearson Chi-square, Shapiro-Wilk, Shapiro-Francia, Jarque-Bera, SJ, Robust Jarque-Bera, and also to entropy-based test statistics. From the simulation study results it is concluded that the best performance against asymmetric alternatives with support on the whole real line and alternative distributions with support on the positive real line is achieved by the new test. Other findings derived from the simulation study are that SJ and Robust Jarque-Bera tests are the most powerful ones for symmetric alternatives with support on the whole real line, whereas entropy-based tests are preferable for alternatives with support on the unit interval.

*MSC:* 62F03, 62F10.

*Keywords:* Empirical distribution function, entropy estimator, goodness-of-fit tests, Monte Carlo simulation, Robust Jarque-Bera test, Shapiro-Francia test, SJ test; test for normality.

## 1. Introduction

Let $X_1,\ldots,X_n$ be a $n$ independent an identically distributed (iid) random variables with continuous cumulative distribution function (cdf) $F(.)$ and probability density function (pdf) $f(.)$. All along the paper, we will denote the order statistic by $(X_{(1)},\ldots,X_{(n)})$. Based on the observed sample $x_1,\ldots,x_n$, we are interested in the following goodness-of-fit test for a location-scale family:

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$$\begin{cases} H_0: F \in \mathscr{F} \\ H_1: F \notin \mathscr{F} \end{cases} \tag{1}$$

where $\mathscr{F} = \left\{F_0(.;\boldsymbol{\theta}) = F_0\left(\frac{x-\mu}{\sigma}\right) \mid \boldsymbol{\theta} = (\mu,\sigma) \in \Theta\right\}$, $\Theta = \mathbb{R} \times (0,\infty)$ and $\mu$ and $\sigma$ are unspecified. The family $\mathscr{F}$ is called location-scale family, where $F_0(.)$ is the standard case for $F_0(.;\boldsymbol{\theta})$ for $\boldsymbol{\theta} = (0,1)$. Suppose that $f_0(x;\boldsymbol{\theta}) = \frac{1}{\sigma} f_0\left(\frac{x-\mu}{\sigma}\right)$ is the corresponding pdf of $F_0(x;\boldsymbol{\theta})$.

The goodness-of-fit test problem for location-scale family described in (1) has been discussed by many authors. For instance, Zhao and Xu (2014) considered a random distance between the sample order statistic and the quasi sample order statistic derived from the null distribution as a measure of discrepancy. On the other hand, Alizadeh and Arghami (2012) used a test based on the minimum Kullback-Leibler distance. The Kullback-Leibler divergence measure is a special case of a $\phi$-divergence measure (2) for $\phi(x) = x\log(x) - x + 1$ (see p. 5 of Pardo, 2006 for details). Also $\phi$-divergence is a special case of the $\phi$-disparity measure. The $\phi$-disparity measure between two pdf's $f_0$ and $f$ is defined by

$$D_\phi(f_0, f) = \int \phi\left(\frac{f_0(x;\boldsymbol{\theta})}{f(x)}\right) f(x)\, dx, \tag{2}$$

where $\phi : (0,\infty) \to [0,\infty)$ is assumed to be continuous, decreasing on $(0,1)$ and increasing on $(1,\infty)$, with $\phi(1) = 0$ (see p. 29 of Pardo, 2006 for details). In $\phi$-divergence, $\phi$ is a convex function.

Inspired by this idea, in this paper we propose a goodness-of-fit statistic to test (1) by considering a new proximity measure between two continuous cdf's. The organization of the paper is as follows. In Section 2 we define the new measure $\mathrm{H}_n$ and study its properties as a goodness-of-fit statistic. In Section 3 we propose a normality test based on $\mathrm{H}_n$ and find its critical values for several sample sizes and different significance levels. In Section 4 we review forty normality tests, including the most traditional ones such as Kolmogorov-Smirnov, Cramér-von Mises, Anderson-Darling, Shapiro-Wilk, Shapiro-Francia, Pearson Chi-square, among others, and in Section 5 we compare their performances to that of our proposal through a wide set of alternative distributions. We also provide an application example where the Kolmogorov-Smirnov test fails to detect the non normality of the sample.

## 2. A new discrepancy measure

In this section we define a discrepancy measure between two continuous cdf's and study its properties as a goodness-of-fit statistic.

**Definition 2.1** *Let X and Y be two absolutely continuous random variables with cdf's $F_0$ and $F$, respectively. We define*

$$D(F_0,F) = \int_{-\infty}^{\infty} h\left(\frac{1+F_0(x;\boldsymbol{\theta})}{1+F(x)}\right) dF(x) = E_F\left[h\left(\frac{1+F_0(X;\boldsymbol{\theta})}{1+F(X)}\right)\right], \tag{3}$$

*where $E_F[.]$ is the expectation under $F$ and $h:(0,\infty)\to\mathbb{R}^+$ is assumed to be continuous, decreasing on $(0,1)$ and increasing on $(1,\infty)$ with an absolute minimum at $x=1$ such that $h(1)=0$.*

**Lemma 2.2** *$D(F_0,F)\geq 0$ and equality holds if and only if $F_0=F$, almost everywhere.*

*Proof.* Using the non-negativity of function $h$, we have $D(F_0,F)\geq 0$. It is clear that $F_0=F$ implies $D(F_0,F)=0$. Conversely, if $D(F_0,F)=0$, since $h$ has an absolute minimum at $x=1$, then $F_0=F$. ∎

Let us return to the goodness-of-fit test problem for a location-scale family described in (1). Firstly, we estimate $\mu$ and $\sigma$ by their maximum likelihood estimators (MLEs), i.e., $\hat{\mu}$ and $\hat{\sigma}$, respectively, and we take $z_i=(x_i-\hat{\mu})/\hat{\sigma}$, $i=1,\ldots,n$. Note that in this family, $F_0(x_i;\hat{\mu},\hat{\sigma})=F_0(z_i)$. Secondly, consider the empirical distribution function (EDF) based on data $x_i$, that is

$$F_n(t)=\frac{1}{n}\sum_{j=1}^{n}\mathrm{I}_{[x_j\leq t]},$$

where $\mathrm{I}_A$ denotes the indicator of an event A. Then, our proposal is based on the ratio of the standard cdf under $H_0$ and the EDF based on the $x_i$'s. Using (3) with $F=F_n$, $D(F_0,F_n)$ can be written as

$$\begin{aligned}\mathrm{H}_n := D(F_0,F_n) &= \int_{-\infty}^{\infty} h\left(\frac{1+F_0(x;\hat{\mu},\hat{\sigma})}{1+F_n(x)}\right) dF_n(x)\\ &= \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_{(i)};\hat{\mu},\hat{\sigma})}{1+F_n(x_{(i)})}\right)\\ &= \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(z_{(i)})}{1+i/n}\right)\end{aligned}$$

Under $H_0$, we expect that $F_0(t;\hat{\mu},\hat{\sigma})\approx F_n(t)$, for every $t\in\mathbb{R}$ and $1+F_0(t;\hat{\mu},\hat{\sigma})\approx 1+F_n(t)$. Note that, since $h(1)=0$, we expect that $h\big((1+F_0(t))/(1+F_n(t))\big)\approx 0$ and thus $\mathrm{H}_n$ will take values close to zero when $H_0$ is true. Therefore, it seems justifiable that $H_0$ must be rejected for large values of $\mathrm{H}_n$. Some standard choices for $h$ are: $h(x) = (x-1)^2/(x+1)^2, x\log(x)-x+1, (x-1)\log(x), |x-1|$ or $(x-1)^2$ (for more examples, see p. 6 of Pardo, 2006 for details).

**Proposition 2.3** *The support of* $\mathrm{H}_n$ *is* $[0, \max(h(1/2), h(2))]$.

*Proof.* Since $F_0(.)$ and $F_n$ are cdf's and take values in $[0,1]$, we have that

$$1/2 \leq \frac{1+F_0(y)}{1+F_n(y)} \leq 2, \quad y \in \mathbb{R}.$$

Thus

$$0 \leq h\left(\frac{1+F_0(y)}{1+F_n(y)}\right) \leq \max(h(1/2), h(2))$$

Finally, since $\mathrm{H_n}$ is the mean of $h(.)$ over the transformed data, the result is obtained. ■

**Proposition 2.4** *The test statistic based on* $\mathrm{H}_n$ *is invariant under location-scale transformations.*

*Proof.* The location-scale family is invariant under the location-scale transformations of the form $g_{c,r}(X_1,\ldots,X_n) = (rX_1+c,\ldots,rX_n+c)$, $c \in \mathbb{R},\ r>0$, which induces similar transformations on $\Theta : g_{c,r}(\boldsymbol{\theta}) = (r\mu+c, r\sigma)$ (See Shao, 2003). The estimator $T_0(X_1,\ldots,X_n)$ for $\mu$ is location-scale invariant if

$$T_0(rX_1+c,\ldots,rX_n+c) = rT_0(X_1,\ldots,X_n)+c, \quad \forall r>0, c\in\mathbb{R},$$

and the estimator $T_1(X_1,\ldots,X_n)$ for $\sigma$ is location-scale invariant if

$$T_1(rX_1+c,\ldots,rX_n+c) = rT_1(X_1,\ldots,X_n), \quad \forall r>0, c\in\mathbb{R}.$$

We know that MLE of $\mu$ and $\sigma$ are location-scale invariant for $\mu$ and $\sigma$, respectively. Therefore under $H_0$, the distribution of $Z_i = (X_i-\hat{\mu})/\hat{\sigma}$ does not depend on $\mu$ and $\sigma$.

If $G_n$ is the EDF based on data $z_i$, then

$$G_n(z_i) = \frac{1}{n}\sum_{j=1}^{n} \mathrm{I}_{[z_j \leq z_i]} = \frac{1}{n}\sum_{j=1}^{n} \mathrm{I}_{[x_j \leq x_i]} = F_n(x_i),$$

therefore

$$\mathrm{H}_n = \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_{(i)};\hat{\mu},\hat{\sigma})}{1+F_n(x_{(i)})}\right) = \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(z_{(i)})}{1+G_n(z_{(i)})}\right).$$

Since the statistic $\mathrm{H}_n$ is a function of $z_i$, $i=1,\ldots,n$, is location-scale invariant. As a consequence, the null distribution of $\mathrm{H}_n$ does not depend on the parameters $\mu$ and $\sigma$. ■

**Proposition 2.5** *Let $F_1$ be an arbitrary continuous cdf in $H_1$. Then under the assumption that the observed sample have cdf $F_1$, the test based on* $\mathrm{H}_n$ *is consistent.*

*Proof.* Based on Glivenko-Cantelli theorem, for $n$ large enough, we have that $F_n(x) \simeq F_1(x)$, for all $x \in \mathbb{R}$. Also $\hat{\mu}$ and $\hat{\sigma}$ are MLEs of $\mu$ and $\sigma$, respectively, and hence are consistent. Therefore

$$\begin{aligned}
\mathrm{H}_n &= \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_{(i)};\hat{\mu},\hat{\sigma})}{1+F_n(x_{(i)})}\right) = \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_i;\hat{\mu},\hat{\sigma})}{1+F_n(x_i)}\right) \\
&\simeq \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_i;\hat{\mu},\hat{\sigma})}{1+F_1(x_i)}\right) \simeq \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_i,\mu,\sigma)}{1+F_1(x_i)}\right) \\
&\to E_{F_1}\left[h\left(\frac{1+F_0(X,\mu,\sigma)}{1+F_1(X)}\right)\right] =: D(F_0,F_1), \text{ as } n\to\infty,
\end{aligned}$$

where $E_{F_1}[.]$ is the expectation under $F_1$, and $\mu$ and $\sigma^2$ are, respectively, the expectation and variance of $F_1$. Note that the convergence holds by the law of large numbers and $D(F_0,F_1)$ is a divergence between $F_0$ and $F_1$. So the test based on $\mathrm{H}_n$ is consistent. ■

## 3. A normality test based on $\mathrm{H}_n$

Many statistical procedures are based on the assumption that the observed data are normally distributed. Consequently, a variety of tests have been developed to check the validity of this assumption. In this section, we propose a new normality test based on $\mathrm{H}_n$.

Consider again the goodness-of-fit testing problem described in (1), where now $f_0(x;\mu,\sigma) = 1/\sqrt{2\pi\sigma^2}e^{-(x-\mu)^2/2\sigma^2}$, $x\in\mathbb{R}$, in which $\mu\in\mathbb{R}$ and $\sigma>0$ are both unknown, and $F_0(.;\mu,\sigma)$ is the corresponding cdf, where $F_0(.)$ is the standard case for $F_0(.;0,1)$.

First we estimate $\mu$ and $\sigma$ by their maximum likelihood estimators (MLEs), i.e., $\hat{\mu} = \bar{x} = 1/n\sum_{i=1}^{n} x_i$ and $\hat{\sigma}^2 = s^2 = 1/(n-1)\sum_{i=1}^{n}(x_i-\bar{x})^2$, respectively. Let $z_i = (x_i-\bar{x})/s$, $i=1,\ldots,n$. Then, the test statistic for normality is:

$$\mathrm{H}_n = \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(x_{(i)},\bar{x},s)}{1+F_n(x_{(i)})}\right) = \frac{1}{n}\sum_{i=1}^{n} h\left(\frac{1+F_0(z_{(i)})}{1+i/n}\right), \tag{4}$$

where

$$h(x) = \left(\frac{x-1}{x+1}\right)^2. \tag{5}$$

Note that $h:(0,\infty)\to\mathbb{R}^+$ is decreasing on $(0,1)$ and increasing on $(1,\infty)$ with an absolute minimum at $x=1$ such that $h(1)=0$ (see Figure 1). We selected this function $h$, because based on simulation study, it is more powerful than other functions $h$. For example, we considered $h_2(x) := x\log(x)-x+1$ for comparison with $h_1(x) := \left(\frac{x-1}{x+1}\right)^2$ (see Tables 6 and 7).

**Corollary 3.1** *The support of* $\mathrm{H}_n$ *is* $[0, 0.11]$.

*Proof.* From Proposition 2.3 and Figure 1, $\max(h(1/2),h(2)) = 0.11$. ■

Table 1 contains the upper critical values of $\mathrm{H}_n$, which have obtained by Monte Carlo from 100000 simulated samples for different sample sizes $n$ and significance levels $\alpha = 0.01, 0.05, 0.1$.

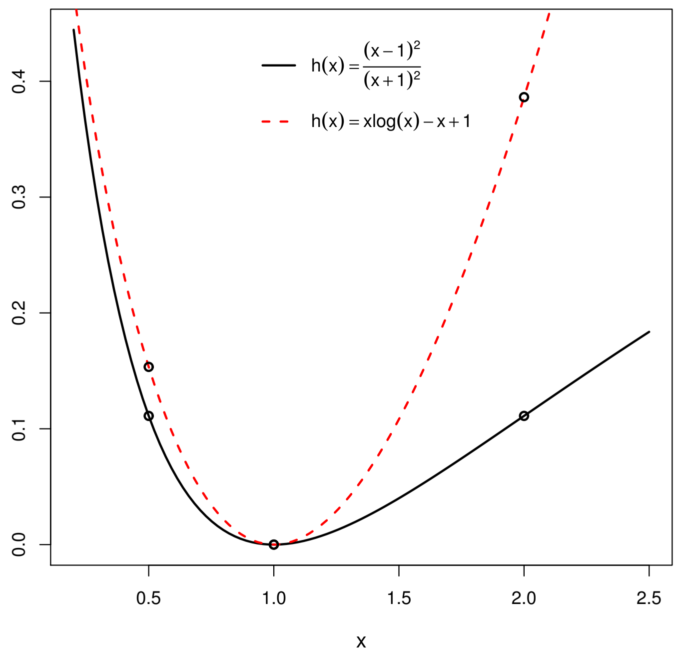


***Figure 1:*** *Plot of function h.*

***Table 1:*** *Critical values of* $\mathrm{H}_n$ *for* $\alpha = 0.01, 0.05, 0.1$.

| $n$ / $\alpha$ | 5 | 6 | 7 | 8 | 9 | 10 | 15 | 20 | 25 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.01 | .0039 | .0035 | .0030 | .0026 | .0023 | .0021 | .0014 | .0011 | .0008 | .0007 | .0005 | .0004 |
| 0.05 | .0030 | .0026 | .0022 | .0019 | .0017 | .0016 | .0010 | .0007 | .0006 | .0005 | .0004 | .0003 |
| 0.10 | .0026 | .0022 | .0019 | .0016 | .0015 | .0013 | .0009 | .0006 | .0005 | .0004 | .0003 | .0002 |

Remember that, $\mathrm{H}_n$ is expected to take values close to zero when $H_0$ is true. Hence, $H_0$ will be rejected for large values of $\mathrm{H}_n$. Also $\mathrm{H}_n$ is invariant under location-scale transformations and consistent under the assumption $H_1$, respectively, from Propositions 2.4 and 2.5.

## 4. Normality tests under evaluation

Comparison of the normality tests has received attention in the literature The goodness-of-fit tests have been discussed by many authors including Shapiro et al. (1968), Poitras (2006), Yazici and Yolacan (2007), Krauczi (2009), Romao et al. (2010), Yap and Sim (2010) and Alizadeh and Arghami (2011).

In this section we consider a large number (forty) of recent and classical statistics that have been used to test normality and in Section 5 we compare their performances with that of $\mathrm{H}_n$. In the following we prefer to keep the original notation for each statistic. Concerning the notation, let $x_1, x_2, \ldots, x_n$ be a random sample of size $n$ and $x_{(1)}, x_{(2)}, \ldots, x_{(n)}$ the corresponding order statistic. Also consider the sample mean, variance, skewness and kurtosis, defined by

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \qquad s^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2, \qquad \sqrt{b_1} = \frac{m_3}{(m_2)^{3/2}}, \qquad b_2 = \frac{m_4}{(m_2)^2},$$

respectively, where the $j$-th central moment $m_j$ is given by $m_j = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^j$ and finally consider $z_{(i)} = (x_{(i)} - \bar{x})/s$, for $i = 1, \ldots, n$.

1. Vasicek's entropy estimator (Vasicek, 1976):

$$\mathrm{KL}_{mn} = \frac{\exp\{\mathrm{HV}_{mn}\}}{s}$$

where

$$\mathrm{HV}_{mn} = \frac{1}{n}\sum_{i=1}^{n} \ln\left\{\frac{n}{2m}\left(X_{(i+m)} - X_{(i-m)}\right)\right\}, \tag{6}$$

$m < n/2$ is a positive integer and $X_{(i)} = X_{(1)}$ if $i < 1$ and $X_{(i)} = X_{(n)}$ if $i > n$. $H_0$ is rejected for small values of KL. Vasicek (1976) showed that the maximum power for KL was typically attained by choosing $m = 2$ for $n = 10$, $m = 3$ for $n = 20$ and $m = 4$ for $n = 50$. The lower-tail 5%-significance values of KL for $n = 10, 20$ and 50 are 2.15, 2.77 and 3.34, respectively.

2. Ebrahimi's entropy estimator (Ebrahimi, Pflughoeft and Soofi, 1994):

$$\mathrm{TE}_{mn} = \frac{\exp\{\mathrm{HE}_{mn}\}}{s},$$

where

$$\mathrm{HE}_{mn} = \frac{1}{n}\sum_{i=1}^{n} \ln\left\{\frac{n}{c_i m}\left(X_{(i+m)} - X_{(i-m)}\right)\right\}, \tag{7}$$

and $c_i = (1 + \frac{i-1}{m})\mathrm{I}_{[1,m]}(i) + 2\mathrm{I}_{[m+1,n-m]}(i) + (1 + \frac{n-i}{m})\mathrm{I}_{[n-m+1,n]}(i)$. Ebrahimi et al. (1994) proved the linear relationship between their estimator and (6). Thus for fixed values of $n$ and $m$, the tests based on (6) and (7) have the same power.

3. Nonparametric distribution function of Vasicek's estimator:

$$\mathrm{TV}_{mn} = \log\sqrt{2\pi\hat{\sigma}_v^2} + 0.5 - \mathrm{HV}_{mn},$$

where $\mathrm{HV}_{mn}$ was defined in (6), $\hat{\sigma}_v^2 = \mathrm{Var}_{g_v}(X)$, and

$$g_v(x) = \begin{cases} 0 & x < \xi_1 \ \text{ or } \ x > \xi_{n+1}, \\ \frac{2m}{n(x_{(i+m)} - x_{(i-m)})} & \xi_i < x \leq \xi_{i+1} \ \ i = 1, \ldots, n, \end{cases}$$

where $\xi_i = \left(x_{(i-m)} + \cdots + x_{(i+m-1)}\right)/2m$. $H_0$ is rejected for large values of $\mathrm{TV}_{mn}$. (See Park, 2003).

4. Nonparametric distribution function of Ebrahimi estimator:

$$\mathrm{TE}_{mn} = \log\sqrt{2\pi\hat{\sigma}_e^2} + 0.5 - \mathrm{HE}_{mn},$$

where $\mathrm{HE}_{mn}$ was defined in (7), $\hat{\sigma}_e^2 = \mathrm{Var}_{g_e}(X)$ and

$$g_e(x) = \begin{cases} 0 & x < \eta_1 \ \text{ or } \ x > \eta_{n+1} \\ \frac{1}{n(\eta_{i+1} - \eta_i)} & \eta_i < x \leq \eta_{i+1} \ \ i = 1, \ldots, n, \end{cases}$$

with

$$\eta_i = \begin{cases} \xi_{m+1} - \frac{1}{m+k-1}\sum_{k=i}^{m}\big(x_{(m+k)} - x_{(1)}\big) & 1 \le i \le m, \\ \frac{1}{2m}\left(x_{(i-m)} + \cdots + x_{(i+m-1)}\right) & m+1 \le i \le n-m+1, \\ \xi_{n-m+1} + \frac{1}{n+m-k+1}\sum_{k=n-m+2}^{i}\big(x_{(n)} - x_{(k-m-1)}\big) & n-m+2 \le i \le n+1, \end{cases}$$

and $\xi_i = \left(x_{(i-m)} + \cdots + x_{(i+m-1)}\right)/2m$. $H_0$ is rejected for large values of $\text{TE}_{mn}$. (See Park, 2003).

5. Nonparametric distribution function of Alizadeh and Arghami estimator (Alizadeh Noughabi and Arghami, 2010, 2013):

$$\text{TA}_{mn} = \log\sqrt{2\pi\hat{\sigma}_a^2} + 0.5 - \text{HA}_{mn},$$

where

$$\text{HA}_{mn} = \frac{1}{n}\sum_{i=1}^{n}\ln\left\{\frac{n}{a_i m}\left(X_{(i+m)} - X_{(i-m)}\right)\right\},$$

with $a_i = \text{I}_{[1,m]}(i) + 2\text{I}_{[m+1,n-m]}(i) + \text{I}_{[n-m+1,n]}(i)$, $\hat{\sigma}_a^2 = \text{Var}_{g_a}(X)$ and

$$g_a(x) = \begin{cases} 0 & x < \eta_1 \text{ or } x > \eta_{n+1}, \\ \frac{1}{n(\eta_{i+1} - \eta_i)} & \eta_i < x \le \eta_{i+1} \quad i = 1, \ldots, n, \end{cases}$$

with

$$\eta_i = \begin{cases} \xi_{m+1} - \frac{1}{m}\sum_{k=i}^{m}\big(x_{(m+k)} - x_{(1)}\big) & 1 \le i \le m, \\ \frac{1}{2m}\left(x_{(i-m)} + \cdots + x_{(i+m-1)}\right) & m+1 \le i \le n-m+1, \\ \xi_{n-m+1} + \frac{1}{m}\sum_{k=n-m+2}^{i}\big(x_{(n)} - x_{(k-m-1)}\big) & n-m+2 \le i \le n+1, \end{cases}$$

and $\xi_i = \left(x_{(i-m)} + \cdots + x_{(i+m-1)}\right)/2m$. Also $m = [\sqrt{n} + 1]$. $H_0$ is rejected for large values of $\text{TA}_{mn}$. The upper-tail 5%-significance values of TA for $n = 10, 20$ and 50 are 0.4422, 0.2805 and 0.1805, respectively.

6. Dimitriev and Tarasenko's entropy estimator (Dimitriev and Tarasenko, 1973):

$$\text{TD}_{mn} = \frac{\exp\{\text{HD}_{mn}\}}{s}$$

where

$$\mathrm{HD}_{mn} = -\int_{-\infty}^{\infty} \ln(\hat{f}(x))\hat{f}(x)\, dx,$$

where $\hat{f}(x)$ is the kernel density estimation of $f(x)$ given by

$$\hat{f}(X_i) = \frac{1}{nh}\sum_{j=1}^{n} k\left(\frac{X_i - X_j}{h}\right), \tag{8}$$

where $k$ is a kernel function satisfying $\int_{-\infty}^{\infty} k(x)\, dx = 1$ and $h$ is a bandwidth. The kernel function $k$ being the standard normal density function and the bandwidth $h = 1.06\hat{\sigma}n^{-1/5}$. $H_0$ is rejected for small values of $\mathrm{TD}_{mn}$.

7. Corea's entropy estimator (Corea, 1995):

$$\mathrm{TC}_{mn} = \frac{\exp\{\mathrm{HC}_{mn}\}}{s},$$

where

$$\mathrm{HC}_{mn} = -\frac{1}{n}\sum_{i=1}^{n} \ln\left\{\frac{\sum_{j=i-m}^{i+m}\left(X_{(j)} - \tilde{X}_{(i)}\right)(j-i)}{n\sum_{j=i-m}^{i+m}\left(X_{(j)} - \tilde{X}_{(i)}\right)^2}\right\}$$

and $\tilde{X}_{(i)} = \sum_{j=i-m}^{i+m} X_{(j)}/(2m+1)$. $H_0$ is rejected for small values of $\mathrm{TC}_{mn}$.

8. Van Es's entropy estimator (Van Es, 1992):

$$\mathrm{TEs}_{mn} = \frac{\exp\{\mathrm{HEs}_{mn}\}}{s},$$

where

$$\mathrm{HEs}_{mn} = \frac{1}{n-m}\sum_{i=1}^{n-m}\left\{\ln\left(\frac{n+1}{m}(X_{(i+m)} - X_{(i)})\right)\right\} + \sum_{k=m}^{n}\frac{1}{k} + \ln(m) - \ln(n+1).$$

$H_0$ is rejected for small values of $\mathrm{TEs}_{mn}$.

9. Zamanzade and Arghami's entropy estimator (Zamanzade and Arghami, 2012):

$$\mathrm{TZ1}_{mn} = \frac{\exp\{\mathrm{HZ1}_{mn}\}}{s},$$

where $\mathrm{HZ1}_{mn} = \frac{1}{n}\sum_{i=1}^{n}\ln(b_i)$, with

$$b_i = \frac{X_{(i+m)} - X_{(i-m)}}{\sum_{j=k_1(i)}^{k_2(i)-1}(\hat{f}(X_{(j+1)}) + \hat{f}(X_{(j)}))(X_{(j+1)} - X_{(j)})/2} \tag{9}$$

where $\hat{f}$ is defined as in (8) with the kernel function $k$ being the standard normal density function and the bandwidth $h = 1.06\hat{\sigma}n^{-1/5}$. $H_0$ is rejected for small values of TZ1. For $n = 10, 20$ and 50, the lower-tail 5%-significance critical values are 3.403, 3.648 and 3.867.

10. Zamanzade and Arghami's entropy estimator (Zamanzade and Arghami, 2012):

$$\mathrm{TZ2}_{mn} = \frac{\exp\{\mathrm{HZ2}_{mn}\}}{s},$$

where $\mathrm{HZ2}_{mn} = \sum_{i=1}^{n} w_i \ln(b_i)$, being coefficients $b_i$'s were defined in (9) and

$$w_i = \begin{cases} (m+i-1)/\sum_{i=1}^{n} w_i & 1 \le i \le m, \\ 2m/\sum_{i=1}^{n} w_i & m+1 \le i \le n-m, \qquad i = 1,\ldots,n, \\ (n-i+m)/\sum_{i=1}^{n} w_i & n-m+1 \le i \le n, \end{cases}$$

are weights proportional to the number of points used in computation of $b_i$'s. $H_0$ is rejected for small values of TZ2. For $n = 10, 20$ and 50, the lower-tail 5%-significance critical values are 3.321, 3.520 and 3.721.

11. Zhang and Wu's statistics (Zhang and Wu, 2005):

$$Z_{\mathrm{K}} = \max_{1\le i\le n}\left[(i-0.5)\ln\frac{i-0.5}{nF_0(Z_{(i)})} + (n-i+0.5)\ln\frac{n-i+0.5}{n(1-F_0(Z_{(i)}))}\right],$$

$$Z_{\mathrm{C}} = \sum_{i=1}^{n}\left(\log\frac{(1/F_0(Z_{(i)})-1)}{(n-0.5)/(i-0.75)-1}\right)^2,$$

and

$$Z_{\mathrm{A}} = -\sum_{i=1}^{n}\left(\frac{\log F_0(Z_{(i)})}{n-i+0.5} + \frac{\log(1-F_0(Z_{(i)}))}{i-0.5}\right),$$

The null hypothesis $H_0$ is rejected for large values of the three test statistics.

12. Classical test statistics for normality based skewness and kurtosis from D'Agostino and Pearson (D'Agostino and Pearson, 1973):

$$\sqrt{b_1} = \frac{m_3}{(m_2)^{3/2}}, \qquad b_2 = \frac{m_4}{(m_2)^2},$$

The null hypothesis $H_0$ is rejected for both small and large values of the two test statistics.

13. Transformed skewness and kurtosis statistic from D'Agostino et al. (1990):

$$\mathrm{K}^2 = \left[Z(\sqrt{b_1})\right]^2 + [Z(b_2)]^2,$$

where

$$Z(\sqrt{b_1}) = \frac{\log(Y/c + \sqrt{(Y/c)^2+1})}{\sqrt{\log(w)}},$$

$$Z(b_2) = \left[\left(1 - \frac{2}{9A}\right) - \sqrt[3]{\frac{1-2/A}{1+y\sqrt{2/(A-4)}}}\right]\sqrt{\frac{9A}{2}},$$

where

$$c_1 = 6 + 8/c_2(2/c_2 + \sqrt{1+4/c_2^2}),$$

$$c_2 = (6(n^2-5n+2)/(n+7)(n+9))\sqrt{6(n+3)(n+5)/n(n-2)(n-3)},$$

$$c_3 = (b_2 - 3(n-1)/(n+1))/\sqrt{24n(n-2)(n-3)/(n+1)^2(n+3)(n+5)}.$$

and

$$Y = \sqrt{b_1}\sqrt{\frac{(n+1)(n+3)}{6(n-2)}}, \qquad w^2 = \sqrt{2\beta_2 - 1} - 1,$$

$$\beta_2 = \frac{3(n^2+27n-70)(n+1)(n+3)}{(n-2)(n+5)(n+7)(n+9)}; \quad c = \sqrt{\frac{2}{(w^2-1)}}.$$

Transformed skewness $Z(\sqrt{b_1})$ and transformed kurtosis $Z(b_2)$ is obtained by D'Agostino (1970) and Anscombe and Glynn (1983), respectively. The null hypothesis $H_0$ is rejected for large values of $\mathrm{K}^2$.

14. Transformed skewness and kurtosis statistic by Doornik and Hansen (1994):

$$\mathrm{DH} = \left[Z(\sqrt{b_1})\right]^2 + z_2^2,$$

where

$$z_2 = \left[\left(\frac{\xi}{2a}\right)^{1/3} - 1 + \frac{1}{9a}\right]\sqrt{9a},$$

and

$$\xi = (b_2 - 1 - b_1)2k,$$

$$k = \frac{(n+5)(n+7)(n^3+37n^2+11n-313)}{12(n-3)(n+1)(n^2+15n-4)},$$

$$a = \frac{(n+5)(n+7)\left((n-2)(n^2+27n-70)+b_1(n-7)(n^2+2n-5)\right)}{6(n-3)(n+1)(n^2+15n-4)},$$

Transformed kurtosis $z_2$ is obtained by Shenton and Bowman (1977). The null hypothesis $H_0$ is rejected for large values of DH.

15. Bonett and Seier's statistic (Bonett and Seier, 2002):

$$\mathrm{Z_w} = \frac{\sqrt{n+2}(\hat{w}-3)}{3.54},$$

where $\hat{w} = 13.29\left(\ln\sqrt{m_2} - \log\left(n^{-1}\sum_{i=1}^{n}|x_i - \bar{x}|\right)\right)$. $H_0$ is rejected for both small and large values of $\mathrm{Z_w}$.

16. D'Agostino's statistic (D'Agostino, 1971):

$$\mathrm{D} = \frac{\sum_{i=1}^{n}(i-(n+1)/2)X_{(i)}}{n^2\sqrt{\sum_{i=1}^{n}\left(x_{(i)}-\bar{X}\right)^2}},$$

$H_0$ is rejected for both small and large values of D.

17. Chen and Shapiro's statistic (Chen and Shapiro, 1995):

$$\mathrm{QH} = \frac{1}{(n-1)s}\sum_{i=1}^{n-1}\frac{X_{(i+1)}-X_{(i)}}{M_{(i+1)}-M_{(i)}},$$

where $M_i = \Phi^{-1}((i-0.375)/(n+0.25))$, where $\Phi$ is the cdf of a standard normal random variable. $H_0$ is rejected for small values of QH.

18. Filliben's statistic (Filliben, 1975):

$$\mathrm{r} = \frac{\sum_{i=1}^{n} x_{(i)} M_{(i)}}{\sqrt{\sum_{i=1}^{n} M_{(i)}^2}\sqrt{(n-1)s^2}},$$

where $M_{(i)} = \Phi^{-1}(m_{(i)})$ and $m_{(1)} = 1-0.5^{1/n}$, $m_{(n)} = 0.5^{1/n}$ and $m_{(i)} = (i-0.3175)/(n+0.365)$ for $i = 2,\ldots,n-1$. $H_0$ is rejected for small values of r.

19. del Barrio et al.'s statistic (del Barrio et al., 1999):

$$\mathrm{R}_n = 1 - \frac{\left(\sum_{k=1}^{n} X_{(k)} \int_{(k-1)/n}^{k/n} F_0^{-1}(t)\,dt\right)^2}{m_2},$$

where $m_2$ is the sample standardized second moment. $H_0$ is rejected for large values of $\mathrm{R}_n$.

20. Epps and Pulley statistic (Epps and Pulley, 1983):

$$\mathrm{T}_{\mathrm{EP}} = \frac{1}{\sqrt{3}} + \frac{1}{n^2}\sum_{k=1}^{n}\sum_{j=1}^{n} \exp\left(\frac{-(X_j - X_k)^2}{2m_2}\right) - \frac{\sqrt{2}}{n}\sum_{j=1}^{n} \exp\left(\frac{-(X_j - \bar{X})^2}{4m_2}\right),$$

where $m_2$ is the sample standardized second moment. $H_0$ is rejected for large values of $\mathrm{T}_{\mathrm{EP}}$.

21. Martinez and Iglewicz's statistic (Martinez and Iglewicz, 1981):

$$\mathrm{I}_n = \frac{\sum_{i=1}^{n}(X_i - M)^2}{(n-1)S_b^2},$$

where $M$ is is the sample median and

$$S_b^2 = \frac{n\sum_{|\tilde{Z}_i|<1}(X_i - M)^2(1-\tilde{Z}_i^2)^4}{\left(\sum_{|\tilde{Z}_i|<1}(1-\tilde{Z}_i^2)(1-5\tilde{Z}_i^2)\right)^2},$$

with $\tilde{Z}_i = (X_i - M)/(9A)$ for $|\tilde{Z}_i| < 1$ and $\tilde{Z}_i = 0$ otherwise, and $A$ is the median of $|X_i - M|$. $H_0$ is rejected for large values of $\mathrm{I_n}$.

22. deWet and Venter statistic (de Wet and Venter, 1972):

$$\mathrm{E}_n = \sum_{i=1}^{n} \left( X_{(i)} - \bar{X} - s\Phi^{-1}\left(\frac{i}{n+1}\right)\right)^2 \Big/ s^2.$$

$H_0$ is rejected for large values of $\mathrm{E_n}$.

23. Optimal test (Csörgo and Révész, 1971):

$$\mathrm{M}_n = \sum_{i=1}^{n} \left( X_{(i)} - \bar{X} - s\Phi^{-1}\left(\frac{i}{n+1}\right)\right)^2 \phi\left(\Phi^{-1}\left(\frac{i}{n+1}\right)\right) \left[\Phi^{-1}\left(\frac{i}{n+1}\right)\right]^{\lambda-1}.$$

$H_0$ is rejected for large values of $\mathrm{M}_n$.

24. Pettitt statistic (Pettitt, 1977):

$$\mathrm{Q}_n = \sum_{i=1}^{n} \left( \Phi\left(\frac{X_{(i)} - \bar{X}}{s}\right) - \frac{i}{n+1}\right)^2 \left[\phi\left(\Phi^{-1}\left(\frac{i}{n+1}\right)\right)\right]^{-2}.$$

$H_0$ is rejected for large values of $\mathrm{Q_n}$.

25. Three test statistics from LaRiccia (1986):

$$\mathrm{T}_{1n} = C_{1n}^2/(s^2 B_{1n}), \qquad \mathrm{T_{2n}} = C_{2n}^2/(s^2 B_{2n}), \qquad \mathrm{T_{3n}} = \mathrm{T_{1n}} + \mathrm{T_{2n}},$$

where

$$C_{1n} = \frac{1}{\sqrt{n}} \sum_{i=1}^{n} \left[ W_1\left(\frac{i}{n+1}\right) - A_{1n}\right] X_{(i)},$$
$$C_{2n} = \frac{1}{\sqrt{n}} \sum_{i=1}^{n} \left[ W_2\left(\frac{i}{n+1}\right) - A_{2n}\Phi^{-1}\left(\frac{i}{n+1}\right)\right] X_{(i)},$$

Also $W_1(u) = [\Phi^{-1}(u)]^2 - 1$ and $W_2(u) = [\Phi^{-1}(u)]^3 - 3\Phi^{-1}(u)$. The constants $A_{1n}$, $A_{2n}$, $B_{1n}$ and $B_{2n}$ are given in Table 1 from LaRiccia (1986). For all three statistics $H_0$ is rejected for large value.

26. Kolmogorov-Smirnov's (Lilliefors) statistic (Kolmogorov, 1933):

$$\mathrm{KS} = \max\left\{ \max_{1\le j\le n}\left[\frac{j}{n} - F_0(Z_{(j)})\right], \max_{1\le j\le n}\left[F_0(Z_{(j)}) - \frac{j-1}{n}\right]\right\}.$$

Lilliefors (1967) computed estimated critical points for the Kolmogorov-Smirnov's test statistic for testing normality when mean and variance estimated.

27. Kuiper's statistic (Kuiper, 1962):

$$\mathrm{V} = \max_{1\leq j\leq n}\left[\frac{j}{n} - F_0(Z_{(j)})\right] + \max_{1\leq j\leq n}\left[F_0(Z_{(j)}) - \frac{j-1}{n}\right].$$

Louter and Kort (1970) computed estimated critical points for the Kuiper test statistic for testing normality when mean and variance estimated.

28. Cramér-von Mises' statistic (Cramér, 1928 and von Mises, 1931):

$$\mathrm{W}^2 = \frac{1}{12n} + \sum_{j=1}^{n}\left(F_0(Z_{(j)}) - \frac{2j-1}{2n}\right)^2.$$

29. Watson's statistic (Watson, 1961):

$$\mathrm{U}^2 = \mathrm{W}^2 - n\left(\frac{1}{n}\sum_{j=1}^{n} F_0(Z_{(j)}) - \frac{1}{2}\right)^2.$$

30. Anderson-Darling's statistic (Anderson, 1954):

$$\mathrm{A}^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left(\log(F_0(Z_{(i)})) + \log\left(1 - F_0(Z_{(n-i+1)})\right)\right).$$

These classical tests are based on the empirical distribution function and $H_0$ is rejected for large values of KS, V, $\mathrm{W}^2$, $\mathrm{U}^2$ and $\mathrm{A}^2$.

31. Pearson's chi-square statistic (D'Agostino and Stephens, 1986):

$$\mathrm{P} = \sum_{i}(C_i - E_i)^2/E_i,$$

where $C_i$ is the number of counted and $E_i$ is the number of expected observations (under $H_0$) in class $i$. The classes are build is such a way that they are equiprobable under the null hypothesis of normality. The number of classes used for the test is $\lceil 2n^{2/5}\rceil$ where $\lceil . \rceil$ is ceiling function.

32. Shapiro-Wilk's statistic (Shapiro and Wilk, 1965):

$$\mathrm{SW} = \frac{\left(\sum_{i=1}^{[n/2]} a_{(n-i+1)}\left(X_{(n-i+1)} - X_{(i)}\right)\right)^2}{\sum_{i=1}^{n}\left(X_{(i)} - \bar{X}\right)^2},$$

where coefficients $a_i$'s are given by

$$(a_1, \ldots, a_n) = \frac{m^T V^{-1}}{(m^T V^{-1} V^{-1} m)^{1/2}}, \tag{10}$$

and $m^T = (m_1, \ldots, m_n)$ and $V$ are, respectively, the vector of expected values and the covariance matrix of the order statistic of $n$ iid random variables sampled from the standard normal distribution. $H_0$ is rejected for small values of SW.

33. Shapiro-Francia's statistic (Shapiro and Francia, 1972) is a modification of SW. It is defined as

$$\mathrm{SF} = \frac{\left(\sum_{i=1}^{n} b_i X_{(i)}\right)^2}{\sum_{i=1}^{n}(X_{(i)} - \bar{X})^2},$$

where

$$(b_1, \ldots, b_n) = \frac{m^T}{(m^T m)^{1/2}}$$

and $m$ is defined as in (10). $H_0$ is rejected for small values of SF.

34. SJ statistic discussed in Gel, Miao and Gastwirth (2007). It is based on the ratio of the classical standard deviation $\hat{\sigma}$ and the robust standard deviation $J_n$ (average absolute deviation from the median (MAAD)) of the sample data

$$\mathrm{SJ} = \frac{s}{J_n}, \tag{11}$$

where $J_n = \sqrt{\frac{\pi}{2}} \frac{1}{n} \sum_{i=1}^{n} |X_i - M|$ and $M$ is the sample median. $H_0$ is rejected for large values of SJ.

35. Jarque-Bera's statistic (Jarque and Bera, 1980, 1987):

$$\mathrm{JB} = \frac{n}{6} b_1 + \frac{n}{24}(b_2 - 3)^2,$$

where $\sqrt{b_1}$ and $b_2$ are the sample skewness and sample kurtosis, respectively. $H_0$ is rejected for large values of JB.

36. Robust Jarque-Bera's statistic (Gel and Gastwirth, 2008):

$$\mathrm{RJB} = \frac{n}{C_1}\left(\frac{m_3}{J_n^3}\right)^2 + \frac{n}{C_2}\left(\frac{m_4}{J_n^4} - 3\right)^2,$$

where $J_n$ is defined as in (11), $C_1$ and $C_2$ are positive constants. For a 5%-significance level, $C_1 = 6$ and $C_2 = 64$ according to Monte Carlo simulations. $H_0$ is rejected for large values of RJB.

## 5. Simulation study

In this section we study the power of the normality test based on $\mathrm{H_n}$ and compare it with a large number of recent and classical normality tests. To facilitate comparisons of the power of the present test with the powers of the mentioned tests, we select two sets of alternative distributions:

*Set 1.* Alternatives listed in in Esteban et al. (2001).

*Set 2.* Alternatives listed in Gan and Koehler (1990) and Krauczi (2009).

### *Set 1 of alternative distributions*

Following Esteban et al. (2001) we consider the following alternative distributions, that can be classified in four groups:

Group I: Symmetric distributions with support on $(-\infty,\infty)$:

- Standard Normal (N);
- Student's $t$ (t) with 1 and 3 degrees of freedoms;
- Double Exponential (DE) with parameters $\mu = 0$ (location) and $\sigma = 1$ (scale);
- Logistic (L) with parameters $\mu = 0$ (location) and $\sigma = 1$ (scale);

Group II: Asymmetric distributions with support on $(-\infty,\infty)$:

- Gumbel (Gu) with parameters $\alpha = 0$ (location) and $\beta = 1$ (scale);
- Skew Normal (SN) with with parameters $\mu = 0$ (location), $\sigma = 1$ (scale) and $\alpha = 2$ (shape);

Group III: Distributions with support on $(0,\infty)$:

- Exponential (Exp) with mean 1;
- Gamma (G) with parameters $\beta = 1$ (scale) and $\alpha = .5, 2$ (shape);
- Lognormal (LN) with parameters $\mu = 0$ and $\sigma = .5, 1, 2$;
- Weibull (W) with parameters $\beta = 1$ (scale) and $\alpha = .5, 2$ (shape);

Group IV: Distributions with support on $(0,1)$:

- Uniform (Unif);
- Beta (B) with parameters (2,2), (.5,.5), (3,1.5) and (2,1).

### *Set 2 of alternative distributions*

Gan and Koehler (1990) and Krauczi (2009) considered a battery of "difficult alternatives" for comparing normality tests. We also consider them in order to evaluate the sensitivity of the proposed test. Let $U$ and $Z$ denote a $[0,1]$-Uniform and a Standard Normal random variable, respectively.

- Contaminated Normal distribution (CN) with parameters $(\lambda, \mu_1, \mu_2, \sigma)$ given by the cdf $F(x) = (1-\lambda)F_0(x, \mu_1, 1) + \lambda F_0(x, \mu_2, \sigma)$;
- Half Normal (HN) distribution, that is, the distribution of $|Z|$.
- Bounded Johnson's distribution (SB) with parameters $(\gamma, \delta)$ of the random variable $e^{(Z-\gamma)/\delta}/(1+e^{(Z-\gamma)/\delta})$;
- Unbounded Johnson's distribution (UB) with parameters $(\gamma, \delta)$ of the random variable $\sinh((Z-\gamma)/\delta)$;
- Triangle type I (Tri) with density function $f(x) = 1-|t|$, $-1 < t < 1$;
- Truncated Standard Normal distribution at $a$ and $b$ (TN);
- Tukey's distribution (Tu) with parameter $\lambda$ of the random variable $U^\lambda - (1-U)^\lambda$.
- Cauchy distribution with parameters $\mu = 0$ (location), $\sigma = 1$ (scale).
- Chi-squared distribution $\chi^2$ with $k$ degrees of freedom.

Tables 2-3 contain the skewness $(\sqrt{\beta_1})$ and kurtosis $(\beta_2)$ of the previous sets of alternative distributions. Alternatives in *Set 2* are roughly ordered and grouped in five groups according to their skewness and kurtosis values in Table 3. These groups correspond to: symmetric short tailed, symmetric closed to normal, asymmetric short tailed, asymmetric long tailed. Figure 2 illustrates some of the possible shapes of the pdf's of the alternatives in *Set 1* and *Set 2*.

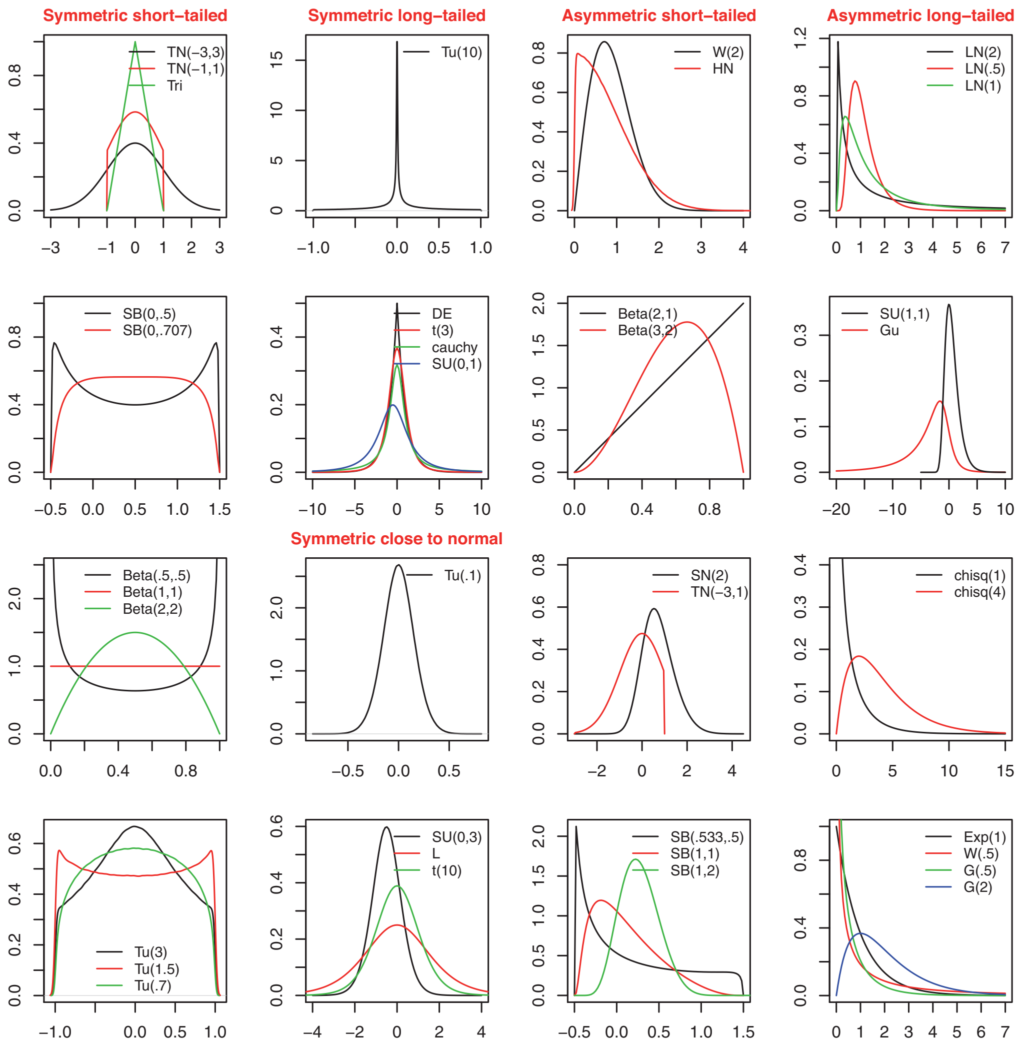


***Figure 2:*** *Plots of alternative distributions in* Set 1 *and* Set 2.

Tables 4-5 contain the estimated value of $\mathrm{H_n}$ (for $h(x) = (x-1)^2/(x+1)^2$ and $h(x) = x\log(x) - x + 1$, respectively), for each alternative distribution, computed as the average value from 10000 simulated samples of sizes $n = 10, 20, 50, 100, 1000$. In the last row of these tables $(n = \infty)$), we show the value of $D(F_0, F_1)$ computed with the the command `integrate` in R Software, with $(\mu)$ and $(\sigma^2)$ being the expectation and variance of $F_1$, respectively. *These tables show consistency of the test statistic* $\mathrm{H}_n$.

Tables 6-7 report the power of the 5% significance level of forty normality tests based on the statistics considered in Section 4 for the *Set 1* of alternatives.

Tables 8-9 contain the power of the 5% significance level test of normality based on the most powerful statistics and the alternatives listed in *Set 2*.

***Table 2:*** *Skewness and kurtosis of alternative distributions in* Set 1.

| | Group I | | | | Group II | | Group III | | | | | | | | Group IV | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t(1) | t(3) | L | DE | Gu | SN(2) | Exp | G(2) | G(.5) | LN(1) | LN(2) | LN(.5) | W(.5) | W(2) | Unif | B(2,2) | B(.5,.5) | B(3,.5) | B(2,1) |
| $\sqrt{\beta_1}$ | 0 | 0 | 0 | 0 | 1.30 | .45 | 2 | 1.41 | 2.83 | 6.18 | 414.36 | 1.75 | 6.62 | .63 | 0 | 0 | 0 | $-1.575$ | $-.57$ |
| $\beta_2$ | — | — | 4.2 | 6 | 5.4 | .31 | 9 | 6 | 15 | 113.94 | 9220560 | 8.90 | 87.72 | 3.25 | 1.8 | 2.14 | 1.5 | 5.22 | 2.4 |

***Table 3:*** *Skewness and kurtosis of alternative distributions in* Set 2.

| | Symmetric | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Short tailed | | | | | | | Close to Normal | | | Long tailed | | |
| | Tu | Tu | Tu | SB | Tri | TN | TN | Tu | SU | t | Tu | SU | caushy |
| | (.7) | (1.5) | (3) | (0,.5) | | $(-1,1)$ | $(-3,3)$ | (.1) | (0,3) | (10) | (10) | (0,1) | |
| $\sqrt{\beta_1}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\beta_2$ | 1.92 | 1.75 | 2.06 | 1.63 | 2.4 | 1.94 | 2.84 | 3.21 | 3.53 | 4 | 5.38 | 36.2 | $\infty$ |

| | Asymmetric | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Short tailed | | | | | Long tailed | | |
| | TN | SB | SB | SB | HN | SU | $\chi^2$ | $\chi^2$ |
| | $(-3,1)$ | (1,1) | (1,2) | (.533,.5) | | (1,1) | (1) | (4) |
| $\sqrt{\beta_1}$ | $-.55$ | .73 | .28 | .65 | .97 | $-5.37$ | 2.83 | 1.41 |
| $\beta_2$ | 2.78 | 2.91 | 2.77 | 2.13 | 3.78 | 93.4 | 15 | 6 |

***Table 4:*** *Estimated value of* $\mathrm{H}_n$ *with* $h_1(x) = (x-1)^2/(x+1)^2$ *under* $H_1$*, based on 10000 simulations for several values of n.*

| | Group I | | | | Group II | | Group III | | | | | | | | Group IV | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t(1) | t(3) | L | DE | Gu | SN(2) | Exp | G(2) | G(.5) | LN(1) | LN(2) | LN(.5) | W(.5) | W(2) | Unif | B(2,2) | B(.5,.5) | B(3,.5) | B(2,1) |
| n | | | | | | | | | | | | | | | | | | | |
| 10 | — | .0011 | .00086 | .0010 | .0011 | .00092 | .0017 | .0013 | .0025 | .00226 | .0040 | .0013 | .0035 | .00097 | .0009 | .00082 | .0012 | .0013 | .0008 |
| 20 | — | .0007 | .00043 | .0006 | .0007 | .00047 | .0014 | .0009 | .0023 | .00213 | .0045 | .0009 | .0036 | .00054 | .0005 | .00041 | .0008 | .0011 | .0005 |
| 50 | — | .0005 | .00018 | .0004 | .0004 | .00022 | .0012 | .0006 | .0022 | .00211 | .0052 | .0007 | .0037 | .00028 | .0003 | .00019 | .0006 | .0011 | .0003 |
| 100 | — | .0004 | .00011 | .0003 | .0003 | .00013 | .0011 | .0006 | .0022 | .00215 | .0056 | .0006 | .0039 | .00019 | .0003 | .00012 | .0006 | .0011 | .0003 |
| 1000 | — | .0004 | .00004 | .0002 | .0002 | .00006 | .0010 | .0005 | .0021 | .00226 | .0066 | .0005 | .0040 | .00012 | .0002 | .00006 | .0005 | .0011 | .0002 |
| ∞ | — | .0004 | .00003 | .0002 | .0002 | .00005 | .0010 | .0005 | .0021 | .00228 | .0074 | .0005 | .0040 | .00011 | .0002 | .00006 | .0005 | .0011 | .0002 |

***Table 5:*** *Estimated value of* $\mathrm{H}_n$ *with* $h_2(x) = x\log(x) - x + 1$ *under* $H_1$*, based on 10000 simulations for several values of n.*

| | Group I | | | | Group II | | Group III | | | | | | | | Group IV | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t(1) | t(3) | L | DE | Gu | SN(2) | Exp | G(2) | G(.5) | LN(1) | LN(2) | LN(.5) | W(.5) | W(2) | Unif | B(2,2) | B(.5,.5) | B(3,.5) | B(2,1) |
| n | | | | | | | | | | | | | | | | | | | |
| 10 | — | .0021 | .00167 | .0019 | .0022 | .0018 | .0034 | .0027 | .0048 | .0044 | .0077 | .0026 | .0065 | .0020 | .0019 | .0017 | .0025 | .0027 | .0017 |
| 20 | — | .0014 | .00086 | .0012 | .0013 | .0009 | .0028 | .0017 | .0045 | .0042 | .0088 | .0018 | .0070 | .0010 | .0011 | .0009 | .0017 | .0024 | .0010 |
| 50 | - | .0010 | .00037 | .0007 | .0008 | .0004 | .0023 | .0013 | .0044 | .0042 | .0106 | .0013 | .0075 | .0005 | .0006 | .0004 | .0013 | .0023 | .0006 |
| 100 | - | .0009 | .00021 | .0006 | .0006 | .0003 | .0022 | .001 | .0043 | .0043 | .0113 | .0012 | .0079 | .0004 | .0005 | .0003 | .0012 | .0023 | .0005 |
| 1000 | — | .0009 | .00007 | .0004 | .0005 | .0001 | .0021 | .0009 | .0043 | .0046 | .0139 | .0010 | .0084 | .0002 | .0004 | .0001 | .0011 | .0023 | .0004 |
| ∞ | — | .0009 | .00006 | .0004 | .0005 | .0001 | .0021 | .0009 | .0043 | .0047 | .0163 | .0010 | .0084 | .0002 | .0004 | .0001 | .0010 | .0023 | .0004 |

***Table 6:*** *Power comparisons for the normality test for* Set 1 *of alternative distributions,* $\alpha = 0.05$, $n = 10$.

| | Group | | I | | | | II | | III | | | | | | | | IV | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | altern. | N | t(1) | t(3) | L | DE | Gu | SN | Exp | G(2) | G(.5) | LN(1) | LN(2) | LN(.5) | W(.5) | W(2) | Unif | B(2,2) | B(.5,.5) | B(3,.5) | B(2,1) |
| 1 | KL | .048 | .442 | .091 | .051 | .091 | .101 | .058 | .416 | .179 | .782 | .552 | .938 | .181 | .931 | .075 | .167 | .082 | .512 | .108 | .173 |
| 2 | TV | .048 | .375 | .082 | .048 | .053 | .092 | .055 | .397 | .151 | .762 | .519 | .933 | .144 | .923 | .073 | **.181** | .084 | **.514** | .656 | .170 |
| 3 | TE | .052 | .460 | .112 | .058 | .077 | .111 | .059 | .454 | .185 | .794 | .581 | .945 | .181 | .935 | .074 | .158 | .071 | .481 | .686 | .164 |
| 4 | TA | .053 | .507 | .134 | .065 | .094 | .124 | .062 | .477 | .213 | **.810** | .616 | **.951** | .208 | **.940** | .080 | .129 | .064 | .451 | **.704** | .162 |
| 5 | TD | .051 | .583 | .201 | .087 | .163 | .154 | .071 | .394 | .222 | .631 | .565 | .869 | .249 | .813 | .076 | .028 | .025 | .080 | .065 | .093 |
| 6 | TC | .054 | .409 | .083 | .047 | .057 | .097 | .053 | .404 | .173 | .786 | .542 | .936 | .171 | .926 | .071 | .170 | **.086** | .489 | .110 | **.182** |
| 7 | TEs | .049 | .591 | .167 | .074 | .140 | .113 | .062 | .330 | .158 | .679 | .485 | .892 | .176 | .876 | .064 | .061 | .037 | .238 | .064 | .092 |
| 8 | TZ1 | .053 | .632 | .212 | .089 | .177 | .145 | .068 | .359 | .209 | .581 | .524 | .846 | .229 | .784 | .074 | .030 | .025 | .078 | .061 | .081 |
| 9 | TZ2 | .051 | .638 | .216 | .091 | .181 | .144 | .066 | .353 | .205 | .572 | .516 | .840 | .228 | .776 | .073 | .026 | .023 | .060 | .058 | .076 |
| 10 | $Z_K$ | .055 | .587 | .174 | .075 | .154 | .126 | .071 | .352 | .180 | .636 | .509 | .885 | .192 | .842 | .079 | .078 | .053 | .221 | .510 | .109 |
| 11 | $Z_C$ | .053 | .580 | .183 | .079 | .154 | .157 | .074 | .450 | .245 | .740 | .606 | .926 | .248 | .898 | .089 | .094 | .044 | .336 | .621 | .130 |
| 12 | $Z_A$ | .053 | .608 | .199 | .083 | .167 | .162 | .071 | .457 | .246 | .744 | .612 | .928 | .255 | .901 | .086 | .050 | .032 | .204 | .621 | .115 |
| 13 | $\sqrt{b_1}$ | .057 | .587 | .219 | .096 | .184 | .165 | .073 | .372 | .226 | .557 | .532 | .928 | .247 | .751 | .088 | .019 | .024 | .035 | .437 | .083 |
| 14 | $b_2$ | .053 | .536 | .170 | .073 | .136 | .113 | .060 | .227 | .148 | .340 | .353 | .907 | .159 | .508 | .072 | .115 | .057 | .270 | .235 | .092 |
| 15 | $K^2$ | .058 | .592 | .220 | .096 | .190 | .154 | .073 | .314 | .197 | .467 | .464 | .754 | .221 | .662 | .082 | .020 | .021 | .065 | .336 | .067 |
| 16 | DH | .055 | .625 | .207 | .084 | .183 | .130 | .067 | .344 | .183 | .590 | .507 | .860 | .195 | .797 | .069 | .071 | .037 | .238 | .467 | .093 |
| 17 | $Z_w$ | .055 | .501 | .150 | .068 | .130 | .075 | .088 | .125 | .091 | .181 | .210 | .416 | .097 | .311 | .055 | .100 | .056 | .215 | .123 | .073 |
| 18 | D | .051 | .584 | .175 | .071 | .142 | .111 | .060 | .270 | .146 | .478 | .434 | .799 | .168 | .717 | .064 | .042 | .044 | .039 | .335 | .061 |
| 19 | QH | .053 | .598 | .189 | .081 | .159 | .160 | .075 | .455 | .245 | .742 | .609 | .928 | .250 | .901 | .090 | .094 | .046 | .321 | .625 | .135 |
| 20 | r | .054 | .635 | .214 | .088 | .187 | .160 | .074 | .421 | .231 | .692 | .578 | .907 | .245 | .868 | .089 | .042 | .031 | .164 | .561 | .099 |
| 21 | $R_n$ | .054 | .609 | .196 | .083 | .167 | .162 | .075 | .448 | .244 | .733 | .604 | .924 | .251 | .894 | .090 | .077 | .042 | .276 | .613 | .125 |
| 22 | $T_{EP}$ | .053 | .602 | .200 | .088 | .170 | .167 | .077 | .427 | .244 | .663 | .587 | .891 | .256 | .842 | .070 | .054 | .040 | .152 | .538 | .115 |
| 23 | $I_n$ | .055 | .157 | .151 | .084 | .151 | .120 | .066 | .209 | .149 | .199 | .215 | .100 | .151 | .134 | .070 | .024 | .025 | .043 | .207 | .065 |
| 24 | $E_n$ | .055 | .638 | .218 | .089 | .193 | .158 | .073 | .407 | .226 | .670 | .567 | .898 | .240 | .852 | .082 | .035 | .028 | .126 | .536 | .091 |
| 25 | $M_n$ | .054 | .631 | .226 | .095 | .198 | .147 | .071 | .326 | .189 | .524 | .484 | .808 | .214 | .733 | .073 | .014 | .020 | .029 | .385 | .061 |
| 26 | $Q_n$ | .053 | .604 | .175 | .074 | .152 | .141 | .071 | .426 | .220 | .728 | .585 | .923 | .222 | .894 | .081 | .094 | .051 | .285 | .610 | .130 |
| 27 | $T_{1n}$ | .054 | .516 | .179 | .083 | .145 | .173 | .072 | .475 | .264 | .726 | .626 | .918 | .274 | .884 | .095 | .036 | .030 | .093 | .605 | .114 |
| 28 | $T_{2n}$ | .053 | .555 | .168 | .072 | .155 | .075 | .055 | .106 | .075 | .167 | .206 | .453 | .088 | .326 | .049 | .090 | .046 | .284 | .105 | .060 |
| 29 | $T_{3n}$ | .057 | .647 | .225 | .093 | .204 | .146 | .070 | .360 | .199 | .625 | .518 | .882 | .216 | .831 | .074 | .039 | .026 | .203 | .487 | .076 |
| 30 | KS | .053 | .581 | .164 | .073 | .148 | .124 | .072 | .312 | .170 | .545 | .469 | .828 | .182 | .761 | .078 | .066 | .051 | .163 | .424 | .103 |
| 31 | V | .050 | .593 | .163 | .071 | .143 | .119 | .065 | .365 | .180 | .662 | .530 | .894 | .188 | .856 | .074 | .087 | .054 | .240 | .540 | .108 |
| 32 | $W^2$ | .052 | .624 | .186 | .080 | .164 | .143 | .073 | .396 | .210 | .674 | .562 | .898 | .220 | .860 | .082 | .083 | .050 | .236 | .552 | .116 |
| 33 | $U^2$ | .052 | .618 | .178 | .076 | .159 | .135 | .071 | .382 | .200 | .661 | .547 | .893 | .211 | .853 | .081 | .091 | .056 | .260 | .540 | .120 |
| 34 | $A^2$ | .051 | .619 | .190 | .083 | .165 | .147 | .073 | .417 | .225 | .670 | .578 | .911 | .233 | .877 | .085 | .086 | .048 | .268 | .580 | .126 |
| 35 | P | .042 | .531 | .148 | .083 | .136 | .127 | .080 | .397 | .200 | .704 | .545 | .903 | .199 | .878 | .087 | .086 | .061 | .229 | .594 | .136 |
| 36 | SW | .052 | .597 | .187 | .082 | .159 | .159 | .075 | .451 | .245 | .740 | .608 | .927 | .248 | .899 | .088 | .090 | .045 | .312 | .622 | .133 |
| 37 | SF | .054 | .631 | .214 | .088 | .185 | .161 | .074 | .426 | .234 | .701 | .584 | .912 | .248 | .872 | .085 | .047 | .033 | .183 | .571 | .104 |
| 38 | SJ | .055 | **.655** | .217 | .096 | **.211** | .121 | .068 | .253 | .147 | .429 | .416 | .756 | .176 | .660 | .060 | .012 | .021 | .022 | .285 | .046 |
| 39 | JB | .059 | .600 | .223 | .096 | .192 | .149 | .075 | .352 | .219 | .532 | .511 | .804 | .242 | .731 | .087 | .016 | .021 | .029 | .396 | .073 |
| 40 | RJB | .056 | .644 | **.228** | **.097** | .205 | .165 | .072 | .485 | .189 | .504 | .470 | .784 | .214 | .700 | .076 | .015 | .021 | .025 | .345 | .061 |
| $h_2$ | $H_n$ | .051 | .596 | .173 | .074 | .150 | .190 | .091 | .504 | .285 | .780 | .659 | .940 | .290 | .918 | .114 | .074 | .046 | .218 | .331 | .054 |
| $h_1$ | $H_n$ | .051 | .587 | .169 | .073 | .144 | **.199** | **.095** | **.516** | **.296** | .784 | **.665** | .942 | **.301** | .920 | **.119** | .079 | .049 | .220 | .300 | .047 |

***Table 7:*** *Power comparisons for the normality test for* Set 1 *of alternative distributions,* $\alpha = 0.05$, $n = 20$.

| | Group | | I | | | | II | | III | | | | | | | | IV | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | altern. | N | t(1) | t(3) | L | DE | Gu | SN | Exp | G(2) | G(.5) | LN(1) | LN(2) | LN(.5) | W(.5) | W(2) | Unif | B(2,2) | B(.5,.5) | B(3,.5) | B(2,1) |
| 1 | KL | .045 | .737 | .165 | .051 | .091 | .198 | .073 | .846 | .457 | .992 | .927 | .999 | .404 | **1.00** | .132 | .442 | .131 | .914 | .224 | **.438** |
| 2 | TV | .047 | .684 | .121 | .046 | .062 | .176 | .067 | .830 | .429 | .992 | .910 | **1.00** | .364 | **1.00** | .126 | **.443** | **.136** | **.910** | .980 | .428 |
| 3 | TE | .047 | .786 | .205 | .064 | .129 | .237 | .079 | .865 | .508 | **.993** | .934 | **1.00** | .445 | **1.00** | .143 | .391 | .112 | .891 | **.984** | .423 |
| 4 | TA | .048 | .858 | .301 | .095 | .229 | .279 | .101 | **.870** | .533 | **.993** | **.937** | **1.00** | .485 | **1.00** | .145 | .258 | .064 | .824 | .983 | .358 |
| 5 | TD | .049 | .872 | .371 | .134 | .304 | .310 | .102 | .790 | .507 | .959 | .909 | .997 | .517 | .995 | .148 | .084 | .028 | .408 | .129 | .221 |
| 6 | TC | .047 | .687 | .138 | .043 | .070 | .185 | .076 | .836 | .443 | .991 | .919 | .999 | .386 | .999 | .133 | .438 | .135 | .902 | .225 | .432 |
| 7 | TEs | .054 | .871 | .330 | .114 | .271 | .195 | .073 | .646 | .322 | .955 | .825 | .997 | .360 | .997 | .089 | .076 | .027 | .460 | .069 | .131 |
| 8 | TZ1 | .056 | .885 | .377 | .133 | .309 | .294 | .099 | .745 | .459 | .947 | .895 | .996 | .470 | .994 | .123 | .099 | .028 | .442 | .114 | .200 |
| 9 | TZ2 | .062 | .900 | .402 | .147 | .344 | .282 | .096 | .688 | .416 | .915 | .865 | .994 | .445 | .987 | .110 | .028 | .013 | .145 | .079 | .130 |
| 10 | $Z_K$ | .055 | .861 | .308 | .109 | .252 | .251 | .088 | .797 | .438 | .983 | .906 | .992 | .423 | .999 | .118 | .132 | .054 | .512 | .952 | .253 |
| 11 | $Z_C$ | .050 | .844 | .333 | .121 | .249 | .313 | .104 | .838 | .529 | .983 | .931 | .999 | .520 | .999 | .159 | .231 | .052 | .782 | .953 | .307 |
| 12 | $Z_A$ | .052 | .864 | .347 | .124 | .268 | .323 | .108 | .866 | **.559** | .989 | .943 | .999 | .541 | .999 | .166 | .142 | .032 | .674 | .967 | .318 |
| 13 | $\sqrt{b_1}$ | .052 | .775 | .345 | .135 | .286 | .324 | .114 | .708 | .471 | .891 | .869 | .990 | .508 | .979 | .151 | .006 | .008 | .013 | .762 | .125 |
| 14 | $b_2$ | .049 | .832 | .333 | .111 | .239 | .181 | .076 | .365 | .230 | .544 | .600 | .877 | .279 | .787 | .093 | .324 | .109 | .683 | .316 | .122 |
| 15 | $K^2$ | .048 | .849 | .370 | .139 | .282 | .267 | .100 | .570 | .371 | .777 | .781 | .967 | .418 | .936 | .119 | .133 | .030 | .491 | .587 | .093 |
| 16 | DH | .050 | .871 | .382 | .141 | .316 | .258 | .089 | .730 | .429 | .941 | .888 | .997 | .444 | .994 | .110 | .101 | .024 | .494 | .855 | .186 |
| 17 | $Z_w$ | .049 | .853 | .326 | .108 | .280 | .120 | .062 | .203 | .135 | .340 | .427 | .756 | .173 | .602 | .059 | .225 | .089 | .539 | .160 | .111 |
| 18 | D | .051 | .882 | .347 | .119 | .276 | .202 | .075 | .517 | .280 | .805 | .758 | .984 | .330 | .963 | .086 | .094 | .075 | .031 | .607 | .067 |
| 19 | QH | .053 | .862 | .327 | .115 | .251 | .313 | .103 | .841 | .533 | .983 | .933 | .999 | .520 | .999 | .157 | .229 | .059 | .761 | .957 | .326 |
| 20 | r | .053 | .895 | .389 | .145 | .325 | .311 | .108 | .794 | .492 | .970 | .911 | .998 | .504 | .999 | .145 | .073 | .019 | .460 | .916 | .207 |
| 21 | $R_n$ | .054 | .875 | .353 | .128 | .281 | .320 | .108 | .833 | .528 | .981 | .931 | .999 | .524 | .999 | .158 | .176 | .045 | .683 | .946 | .292 |
| 22 | $T_{EP}$ | .054 | .868 | .332 | .115 | .257 | .309 | .104 | .778 | .502 | .954 | .912 | .998 | .507 | .995 | .147 | .130 | .043 | .478 | .888 | .266 |
| 23 | $I_n$ | .053 | .144 | .268 | .145 | .286 | .216 | .091 | .387 | .289 | .286 | .310 | .038 | .313 | .084 | .095 | .004 | .006 | .013 | .382 | .070 |
| 24 | $E_n$ | .053 | .901 | .398 | .150 | .337 | .302 | .105 | .763 | .467 | .959 | .899 | .998 | .488 | .997 | .135 | .038 | .013 | .326 | ..891 | .169 |
| 25 | $M_n$ | .050 | .894 | .409 | .153 | .339 | .274 | .099 | .661 | .395 | .897 | .841 | .992 | .431 | .984 | .112 | .005 | .004 | .025 | .771 | .087 |
| 26 | $Q_n$ | .053 | .874 | .311 | .105 | .257 | .277 | .092 | .847 | .508 | .988 | .932 | .999 | .486 | .999 | .142 | .176 | .051 | .663 | .963 | .333 |
| 27 | $T_{1n}$ | .050 | .656 | .255 | .106 | .179 | **.345** | .111 | .838 | .569 | .972 | .938 | .999 | **.565** | .999 | .178 | .029 | .018 | .082 | .924 | .246 |
| 27 | $T_{2n}$ | .049 | .866 | .343 | .116 | .296 | .100 | .059 | .150 | .101 | .269 | .362 | .734 | .141 | .554 | .049 | .311 | .079 | .773 | .109 | .119 |
| 27 | $T_{3n}$ | .050 | .897 | .387 | .143 | .330 | .278 | .096 | .779 | .453 | .973 | .905 | .999 | .466 | .999 | .121 | .174 | .032 | .732 | .926 | .225 |
| 30 | KS | .056 | .847 | .268 | .089 | .227 | .214 | .084 | .595 | .338 | .884 | .799 | .992 | .349 | .985 | .109 | .102 | .056 | .377 | .761 | .192 |
| 31 | V | .052 | .863 | .273 | .090 | .236 | .199 | .073 | .697 | .352 | .955 | .859 | .998 | .348 | .997 | .093 | .148 | .063 | .495 | .885 | .205 |
| 32 | $W^2$ | .056 | .880 | .308 | .105 | .265 | .254 | .091 | .732 | .420 | .954 | .883 | .998 | .429 | .996 | .123 | .149 | .056 | .517 | .882 | .237 |
| 33 | $U^2$ | .055 | .878 | .297 | .099 | .261 | .225 | .083 | .694 | .381 | .942 | .862 | .997 | .391 | .995 | .113 | .167 | .064 | .554 | .863 | .230 |
| 34 | $A^2$ | .054 | .880 | .324 | .110 | .268 | .279 | .094 | .780 | .463 | .968 | .906 | .999 | .467 | .998 | .133 | .179 | .056 | .624 | .917 | .269 |
| 35 | P | .049 | .777 | .182 | .067 | .144 | .141 | .063 | .656 | .282 | .956 | .827 | .998 | .267 | .994 | .074 | .082 | .053 | .272 | .880 | .162 |
| 36 | SW | .054 | .867 | .337 | .119 | .266 | .317 | .105 | .840 | .534 | .982 | .933 | .999 | .526 | .999 | .160 | .208 | .053 | .738 | .954 | .314 |
| 37 | SF | .053 | .893 | .383 | .143 | .318 | .313 | .107 | .802 | .498 | .973 | .915 | .998 | .507 | .999 | .148 | .086 | .022 | .499 | .922 | .220 |
| 38 | SJ | .053 | **.915** | .404 | .147 | **.377** | .188 | .078 | .416 | .234 | .676 | .695 | .959 | .301 | .911 | .064 | .003 | .006 | .002 | .435 | .033 |
| 39 | JB | .050 | .864 | .384 | .146 | .300 | .285 | .104 | .630 | .404 | .840 | .825 | .984 | .448 | .964 | .125 | .003 | .004 | .006 | .677 | .080 |
| 40 | RJB | .054 | .906 | **.410** | **.159** | .354 | .266 | .099 | .563 | .357 | .790 | .787 | .977 | .410 | .949 | .106 | .002 | .004 | .004 | .594 | .061 |
| $h_2$ | $H_n$ | .055 | .874 | .302 | .100 | .254 | .322 | .116 | .832 | .540 | .982 | .933 | .999 | .525 | .999 | .176 | .154 | .061 | .524 | .734 | .140 |
| $h_1$ | $H_n$ | .053 | .869 | .293 | .097 | .244 | .330 | **.120** | .835 | .546 | .983 | .934 | .999 | .532 | .999 | **.181** | .156 | .062 | .525 | .709 | .126 |

***Table 8:*** *Power comparisons for the normality test for* Set 2 *of alternative distributions,* $\alpha = 0.05$, $n = 10$.

| | Symmetric | | | | | | | | | | | | | Asymmetric | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Short tailed | | | | | | | Close to Normal | | | Long tailed | | | Short tailed | | | | | Long tailed | | |
| | Tu | Tu | Tu | SB | Tri | TN | TN | Tu | SU | t | Tu | SU | caushy | TN | SB | SB | SB | HN | SU | $\chi^2$ | $\chi^2$ |
| | (.7) | (1.5) | (3) | (0,.5) | | (-1,1) | (-3,3) | (.1) | (0,3) | (10) | (10) | (0,1) | | (-3,1) | (1,1) | (1,2) | (.533,.5) | | (1,1) | (1) | (4) |
| TV | **.122** | **.205** | **.095** | **.313** | **.057** | **.125** | **.053** | .044 | .045 | .057 | .281 | .086 | .369 | .027 | .130 | .055 | **.442** | .206 | .260 | .766 | .171 |
| TA | .086 | .155 | .068 | .244 | .043 | .089 | .047 | .050 | .051 | .048 | .460 | .162 | .496 | **.095** | .143 | .051 | .431 | .177 | .357 | **.814** | .225 |
| $Z_A$ | .040 | .060 | .033 | .101 | .031 | .037 | .043 | .062 | .067 | .080 | .523 | .258 | .608 | .071 | .133 | .050 | .296 | .196 | .438 | .755 | .254 |
| $\sqrt{b_1}$ | .018 | .019 | .017 | .024 | .025 | .017 | .040 | .061 | .069 | .084 | .372 | .255 | .574 | .061 | .101 | .042 | .130 | .156 | .412 | .566 | .221 |
| r | .035 | .050 | .021 | .086 | .031 | .034 | .044 | .064 | .068 | .087 | .595 | .276 | .634 | .070 | .123 | .050 | .253 | .177 | .436 | .704 | .239 |
| $R_n$ | .057 | .094 | .042 | .149 | .035 | .054 | .046 | .061 | .066 | .075 | .552 | .251 | .609 | .073 | .142 | .054 | .323 | .194 | .436 | .743 | .251 |
| $T_{EP}$ | .046 | .067 | .037 | .101 | .035 | .047 | .050 | .063 | .068 | .085 | .480 | .180 | .602 | .072 | .143 | .057 | .271 | .193 | **.448** | .684 | .256 |
| $E_n$ | .029 | .038 | .026 | .067 | .030 | .028 | .044 | .063 | .068 | .090 | .602 | .278 | .639 | .067 | .114 | .048 | .224 | .168 | .433 | .682 | .232 |
| $M_n$ | .015 | .017 | .017 | .020 | .043 | .016 | .045 | .064 | **.075** | .100 | .521 | .287 | .634 | .061 | .087 | .044 | .115 | .137 | .397 | .550 | .200 |
| $T_{1n}$ | .032 | .041 | .026 | .060 | .031 | .030 | .044 | .061 | .063 | .069 | .338 | .220 | .517 | .077 | .140 | .051 | .253 | .204 | .441 | .739 | .266 |
| $T_{3n}$ | .029 | .047 | .026 | .088 | .030 | .030 | .045 | .064 | .072 | .038 | .579 | .288 | .645 | .083 | .093 | .046 | .200 | .139 | .405 | .644 | .198 |
| $A^2$ | .063 | .102 | .049 | .154 | .037 | .063 | .050 | .060 | .064 | .068 | .630 | .245 | .620 | .075 | .137 | .054 | .319 | .182 | .422 | .715 | .234 |
| SW | .064 | .109 | .049 | .170 | .036 | .064 | .046 | .060 | .064 | .074 | .532 | .242 | .598 | .078 | .144 | .054 | .345 | .199 | .433 | .751 | .253 |
| SF | .037 | .055 | .031 | .093 | .030 | .036 | .044 | .063 | .067 | .082 | .588 | .270 | .630 | .070 | .124 | .050 | .261 | .179 | .435 | .709 | .238 |
| SJ | .014 | .016 | .019 | .015 | .032 | .016 | .047 | **.067** | .072 | **.093** | **.678** | .290 | **.660** | .049 | .070 | .046 | .086 | .101 | .360 | .442 | .157 |
| RJB | .015 | .016 | .016 | .018 | .026 | .016 | .045 | .064 | .073 | **.093** | .569 | **.290** | .645 | .057 | .088 | .044 | .105 | .132 | .394 | .504 | .195 |
| $H_n$ | .066 | .094 | .052 | .141 | .047 | .061 | **.053** | .060 | .064 | .060 | .625 | .222 | .592 | .026 | **.208** | **.073** | .416 | **.262** | .264 | .807 | **.315** |

***Table 9:*** *Power comparisons for the normality test for* Set 2 *of alternative distributions,* $\alpha = 0.05$, $n = 20$.

| | Symmetric | | | | | | | | | | | | | Asymmetric | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Short tailed | | | | | | | Close to Normal | | | Long tailed | | | Short tailed | | | | | Long tailed | | |
| | Tu | Tu | Tu | SB | Tri | TN | TN | Tu | SU | t | Tu | SU | caushy | TN | SB | SB | SB | HN | SU | $\chi^2$ | $\chi^2$ |
| | (.7) | (1.5) | (3) | (0,.5) | | (-1,1) | (-3,3) | (.1) | (0,3) | (10) | (10) | (0,1) | | (-3,1) | (1,1) | (1,2) | (.533,.5) | | (1,1) | (1) | (4) |
| TV | **.291** | **.515** | **.188** | **.729** | **.075** | **.268** | **.051** | .042 | .047 | .048 | .724 | .159 | .683 | **.180** | .314 | .070 | **.877** | .458 | .547 | **.993** | .433 |
| TA | .131 | .310 | .083 | .531 | .036 | .122 | .040 | .051 | .065 | .091 | .909 | .376 | .853 | .171 | .307 | .057 | .807 | **.477** | .678 | .992 | .515 |
| $Z_A$ | .064 | .168 | .040 | .343 | .020 | .057 | .037 | .060 | .077 | .103 | .721 | .421 | .859 | .154 | .305 | .058 | .709 | .462 | .714 | .989 | .541 |
| $\sqrt{b_1}$ | .005 | .007 | .008 | .009 | .011 | .006 | .035 | .065 | .084 | .113 | .354 | .401 | .771 | .111 | .190 | .050 | .174 | .307 | .708 | .882 | .446 |
| r | .034 | .084 | .021 | .193 | .017 | .030 | .037 | .066 | .085 | .109 | .851 | .480 | .890 | .105 | .230 | .052 | .534 | .360 | .720 | .966 | .472 |
| $R_n$ | .085 | .198 | .050 | .385 | .028 | .078 | .038 | .059 | .077 | .102 | .817 | .440 | .872 | .135 | .282 | .058 | .681 | .414 | .721 | .980 | .509 |
| $T_{EP}$ | .073 | .149 | .045 | .267 | .034 | .065 | .042 | .058 | .071 | .090 | .807 | .417 | .866 | .129 | .284 | .062 | .580 | .368 | .722 | .952 | .488 |
| $E_n$ | .019 | .047 | .014 | .114 | .015 | .019 | .036 | .067 | .087 | .112 | .859 | .494 | .897 | .094 | .205 | .049 | .444 | .329 | .712 | .957 | .450 |
| $M_n$ | .003 | .005 | .006 | .010 | .011 | .004 | .034 | .067 | .090 | .116 | .774 | .501 | .894 | .076 | .140 | .041 | .191 | .253 | .675 | .895 | .381 |
| $T_{1n}$ | .018 | .029 | .017 | .046 | .020 | .019 | .040 | .057 | .070 | .089 | .261 | .292 | .645 | .152 | .301 | .058 | .448 | .436 | **.723** | .971 | .547 |
| $T_{3n}$ | .074 | .212 | .043 | .409 | .037 | .070 | .039 | .061 | .083 | .110 | .775 | .482 | .896 | .098 | .205 | .045 | .646 | .333 | .695 | .971 | .433 |
| $A^2$ | .105 | .206 | .060 | .374 | .040 | .092 | .048 | .057 | .070 | .084 | .906 | .423 | .878 | .117 | .266 | .064 | .651 | .359 | .704 | .970 | .459 |
| SW | .108 | .250 | .067 | .452 | .034 | .100 | .040 | .058 | .077 | .097 | .805 | .424 | .866 | .143 | .305 | .063 | .723 | .435 | .719 | .982 | .522 |
| SF | .041 | .102 | .025 | .222 | .018 | .036 | .038 | .065 | .084 | .106 | .848 | .477 | .888 | .109 | .242 | .054 | .561 | .372 | .722 | .970 | .482 |
| SJ | .002 | .001 | .005 | .004 | .018 | .003 | .037 | .066 | .086 | .115 | **.930** | **.509** | **.917** | .039 | .065 | .044 | .054 | .109 | .594 | .669 | .227 |
| RJB | .002 | .002 | .004 | .003 | .011 | .003 | .036 | **.068** | **.092** | **.121** | .819 | .507 | .902 | .065 | .119 | .041 | .091 | .206 | .666 | .784 | .348 |
| $H_n$ | .095 | .176 | .058 | .308 | .041 | .082 | .049 | .056 | .065 | .078 | .914 | .384 | .867 | .056 | **.345** | **.083** | .719 | .441 | .574 | .981 | **. 527** |

***Table 10:*** *Ranking from first to the fifth of average powers computed from values in Tables 6-7 for* Set 1 *of alternative distributions.*

| | Group I Symmetric $(-\infty,\infty)$ | | Group II Asymmetric $(-\infty,\infty)$ | | Group III Asymmetric$(0,\infty)$ | | Group IV (0,1) | |
|---|---|---|---|---|---|---|---|---|
| Rank | $n=10$ | $n=20$ | $n=10$ | $n=20$ | $n=10$ | $n=20$ | $n=10$ | $n=20$ |
| 1 | SJ | SJ | $H_n$ | $T_{1n}$ | $H_n$ | $Z_A$ | TV | TV |
| 2 | RJB | RJB | $T_{1n}$ | $H_n$ | TV | $T_{1n}$ | TE | TE |
| 3 | $T_{3n}$ | $M_n$ | $T_{EP}$ | $Z_A$ | A | $H_n$ | TV | TA |
| 4 | $M_n$ | TZ2 | $\sqrt{b_1}$ | $R_n$ | $T_{1n}$ | SW | $Z_C$ | QH |
| 5 | $E_n$ | $E_n$ | $R_n$ | SW | $Z_A$ | QH | QH | $Z_C$ |

***Table 11:*** *Ranking from first to the fifth of average powers computed from values in Tables 8-9 for* Set 2 *of alternative distributions.*

| | Symmetric | | | | | | Asymmetric | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Rank | Short tailed | | Close to Normal | | Long tailed | | Short tailed | | Long tailed | |
| | $n=10$ | $n=20$ | $n=10$ | $n=20$ | $n=10$ | $n=20$ | $n=10$ | $n=20$ | $n=10$ | $n=20$ |
| 1 | TV | TV | $M_n$ | RJB | SJ | SJ | $H_n$ | $H_n$ | $T_{1n}$ | $T_{1n}$ |
| 2 | TA | TA | SJ | $M_n$ | RJB | RJB | TA | TV | SW | SW |
| 3 | SW | $R_n$ | RJB | SJ | $A^2$ | SF | TV | TA | $R_n$ | $R_n$ |
| 4 | $H_n$ | SW | SF | SF | SF | $A^2$ | SW | SW | $H_n$ | TA |
| 5 | $A^2$ | $A^2$ | SW | $T_{3n}$ | $T_{3n}$ | $M_n$ | $R_n$ | $R_n$ | TA | $H_n$ |

Tables 10-11 contain the ranking from first to the fifth of the average powers computed from the values in Tables 6-7 and 8-9, respectively. By average powers we can select the tests that are, on average, most powerful against the alternatives from the given groups.

Power against an alternative distribution has been estimated by the relative frequency of values of the corresponding statistic in the critical region for 10000 simulated samples of size n = 10, 20. The maximum reached power is indicated in bold. For computing the estimated powers of the new test, R software is used. We also use R software for computing Pearson chi-square and Shapiro-Francia tests by the package (nortest), command `pearson.test` and `sf.test`, respectively, and also the package (lawstat), command `sj.test` and `rjb.test` for SJ and Robast Jarque-Bera tests, respectively. For the entropy-based test statistics, powers are taken from Zamanzadeh and Arghami (2012) and Alizadeh and Arghami (2011, 2013). In the case of the test based on $H_n$, we also consider $h_2(x) := x\log(x) - x + 1$ for comparison with $h_1(x) := \left(\frac{x-1}{x+1}\right)^2$.

### *Results and recommendations*

Based on these comparisons, the following recommendations can be formulated for the application of the evaluated statistics for testing normality in practice.

***Set 1* of alternative distributions** (Tables 6-7 and 10): In Group I, for $n = 10$ and 20, it is seen that the tests based on SJ, RJB, $T_{3n}$, TZ2, $M_n$ and $E_n$ are the most powerful whereas the tests based on $I_n$, TV, TC and KL are the least powerful. The difference of powers between KL and the others is substantial. In Group II, for $n = 10$ and 20, it is seen that the tests based on $H_n$, $T_{1n}$, $T_{EP}$, $R_n$, $Z_A$ and $\sqrt{b_1}$ are the most powerful whereas those based on $T_{2n}$, TV, TC, Kl and $Z_w$ are the least powerful. In Group III, the most powerful tests for $n = 10$ are those based on $H_n$, TV, TA and $T_{1n}$, and for $n = 20$, those based on $Z_A$, $T_{1n}$, $H_n$ and SW are the most powerful. On the other hand, the least powerful tests are those based on $I_n$ and $Z_w$ are the least powerful. Finally, in group IV, the results are not in favour of the proposed tests. In this group, for $n = 10$ and 20, the most powerful tests are those based on TV, TE, TA, $Z_C$, $Z_A$ and r, whereas the tests based on $TZ_2$, SJ and RJB are the least powerful. The SJ and RJB show very poor sensitivity against symmetric distributions in $[0,1]$ such as Unif, $B(2,2)$ or $B(.5,.5)$. For example, for $n = 20$, in the case of the $[0,1]$-Unif alternative, the SJ test has a power of .002 while even the $H_n$ test has a power of .156. From Tables 6-7 one can see that the proportion of times that the SJ and RJB statistics lie below the 5% point of the null distribution are greater than those of the $H_n$ statistic.

Note that for the proposed test, the maximum power in Group II and III was typically attained by choosing $h_1$.

From the simulation study implemented for *Set 1* of alternative distributions we can lead to different conclusions from that existing in the literature. New and existing results are reported in Table 12.

***Table 12:*** *Comparison of most powerful tests in Groups I–IV, according to Alizadeh and Arghami (2011, 2013) and Zamanzade and Arghami (2012) with new simulation results.*

| | | | | |
|---|---|---|---|---|
| Alizadeh and Arghami (2011) | JB | SW | KL[a] or SW | KL |
| Alizadeh and Arghami (2013) | $A^2$ | SW | TA | TV[b] |
| Zamanzadeh and Arghami (2012) | TZ2 | TZ2 or TD | TZ1, KL or TD | KL or TC |
| **New simulation study** | SJ or RJB | $H_n$ or $T_{1n}$ | $H_n$ or $Z_A$ | TV or TE |

[a] Statistic based on Vasicek's estimator
[b] Statistic using nonparametric distribution of Vasicek's estimato

***Set 2* of alternative distributions** (Tables 8-9 and 11): For symmetric short-tailed distributions, it is seen that the tests based on TV, TA and SW are the most powerful. For symmetric close to normal and symmetric long tailed distributions, RJB, JB and $M_n$ are the most powerful. For asymmetric short tailed distributions, $H_n$, TV and TA are the

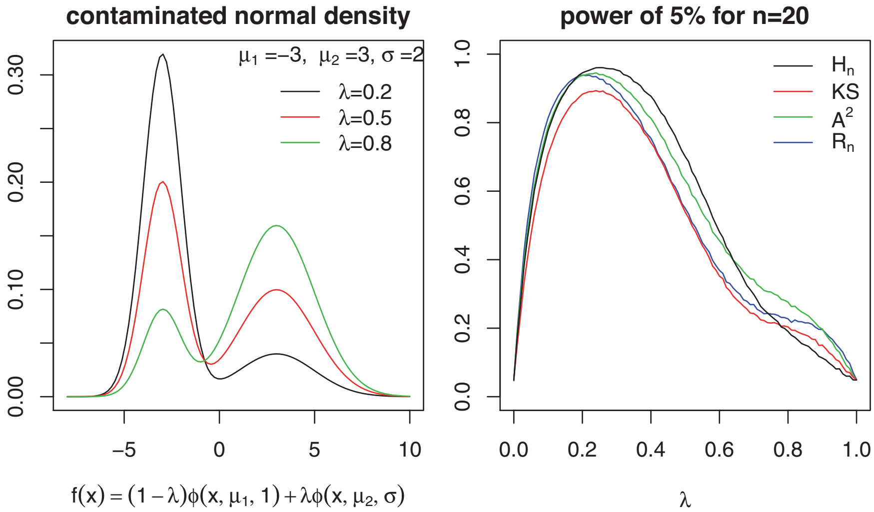


***Figure 3:*** *Left panel: Probability density functions of Contaminated Normal distribution for several values of the parameter* $\lambda$*. Right panel: Power of the tests based on* $\mathrm{H}_n$*,* KS*,* $\mathrm{A}^2$ *and* $\mathrm{R}_n$ *as a function of* $\lambda$ *against alternative* $\mathrm{CN}(\lambda, \mu_1 = -3, \mu_2 = 3, \sigma = 2)$.

most powerful. Finally, for asymmetric long tailed distributions, $\mathrm{T}_{1n}$, SW and $\mathrm{R}_n$ are the most powerful. It is also worth mentioning that the differences between the power of tests based on TV and $\mathrm{H}_n$ in $TN(-3,3)$ alternative are not considerable.

In Figure 3 we compare the power of the tests based on $\mathrm{H}_n$, KS, $\mathrm{A}^2$ and $\mathrm{R}_n$ against a family of Contaminated Normal alternatives $\mathrm{CN}(\lambda, \mu_1 = -3, \mu_2 = 3, \sigma = 2)$. The left panel of Figure 3 contains the probability density functions of Contaminated Normal alternatives $\mathrm{CN}(\lambda, \mu_1 = -3, \mu_2 = 3, \sigma = 1)$, for $\lambda = .2, .5, .8$, whereas the right panel contains the power comparisons for $n = 20$ and $\alpha = 0.05$. We can see the good power results of $\mathrm{H}_n$ for $0.2 < \lambda < 0.6$.

In general, we can conclude that the proposed test $\mathrm{H}_n$ has good performance and therefore can be used in practice.

## *Numerical example*

Finally, we illustrate the performance of the new proposal through the analysis of a real data set. One of the most famous tests of normality among practitioners is the Kolmogorov-Smirnov test, mostly because it is available in any statistical software. However, one of its drawbacks is the low power against several alternatives (see also Grané and Fortiana, 2003; Grané, 2012; Grané and Tchirina, 2013).We would like to emphasize this fact through a numerical example.

Armitage and Berry (1987) provided the weights in ounces of 32 newborn babies(see also data set 3 of Henry, 2002, p. 342). The approximate ML estimators of $\hat{\mu} = 111.75$ and $\hat{\sigma} = \sqrt{331.03} = 18.19$. Also sample skewness and kurtosis are $\sqrt{b_1} = -.64$ and

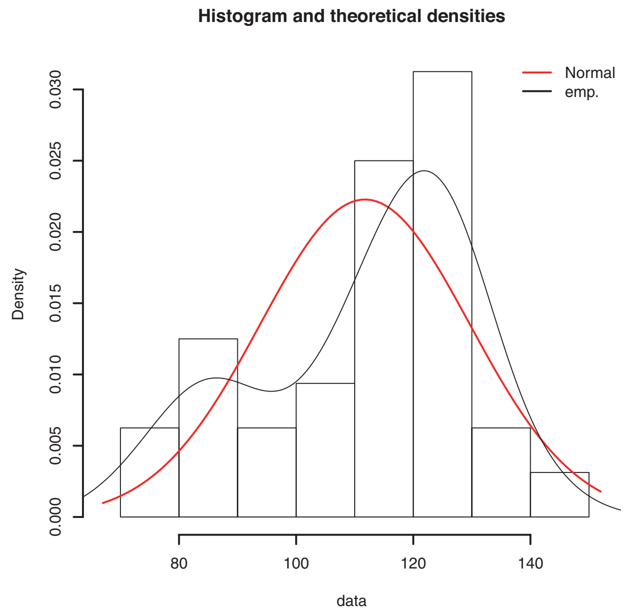


***Figure 4:*** *Histogram and theoretical (normal) distribution for ounces of 32 newborn babies data.*

$b_2 = 2.33$, respectively. From the histogram of these data it can be observed that the birth weights are skewed to the left and may be bimodal (see Figure 4).

When fitting the normal distribution to these data, we find that the KS (Kolmogorov-Smirnov) test does not reject the null hypothesis providing a p-value of 0.093. However with the $\mathrm{H}_n$ statistic we are able to reject the null hypothesis of normality at a 5% significance level, since we obtain $\mathrm{H}_n = .0006$ and the corresponding critical value for $n = 32$ is .00047. Also associated p-values of the $\mathrm{H}_n$, SW (Shapiro-Wilk) and SF (Shapiro-Francia) tests are .015, .024 and .036, respectively. Thus, the non-normality is more pronounced by the new test at 5% level. In Appendix, we provide an R software program, to calculate the $\mathrm{H}_n$ statistics, the critical points and corresponding p-value.

## 6. Conclusions

In this paper we propose a statistic to test normality and compare its performance with 40 recent and classical tests for normality and a wide collection of alternative distributions. As expected (Janssen, 2000), the simulation study shows that none of the statistics under evaluation can be considered to be the best one for all the alternative distributions studied. However, the tests based on RJB or SJ have the best performance for symmetric distributions with the support on $(-\infty, \infty)$ and the same happens to TV or TA for distributions with the support on $(0, 1)$. Regarding our proposal, $\mathrm{H}_n$ and also $\mathrm{T}_{1n}$ are the most powerful for asymmetric distributions with the support on $(-\infty, \infty)$ and distributions with the support on $(0, \infty)$, mainly for small sample sizes.

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## Appendix

```
h=function(x) (x-1)^2/(x+1)^2
Hn=function(x) {x=sort(x);n=length(x);
F=pnorm(x, mean(x), sd(x)*sqrt(n/(n-1)))+1;
Fn=1:n/n+1; mean(h(F/Fn))}

##weights in ounces of 32 newborn babies,
data=c(72,80,81,84,86,87,92,94,103,106,107,111,112,115,116,118,
119,122,123,123,114,125,126,126,126,127,118,128,128,132,133,142)
Hn(data)  ## statistics
n=length(data); B=10000; x=matrix(rnorm(n*B, 0, 1), nrow=B, ncol=n)
H0=apply(x, 1, Hn); Q=quantile(H0, .95); Q  ## critical point
length(H0[H0>Hn(data)])/B  ##p-value
```

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