

## NEW EXTENSIONS OF THE HERMITE-HADAMARD INEQUALITIES BASED ON $\psi$ -HILFER FRACTIONAL INTEGRALS

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ABSTRACT. This article presents the above and below bounds for Midpoint and Trapezoid types inequalities for  $\psi$ -Hilfer fractional integrals with the assistance of the functions whose second derivatives are bounded. We also possess some extensions and generalizations of Hermite–Hadamard inequalities via  $\psi$ -Hilfer fractional integrals with the aid of the functions that have the conditions that will said.

### 1. INTRODUCTION

Inequalities have guided many studies in mathematical topics. Especially the Hermite-Hadamard inequality (H-II) has been the subject of many studies in the literature. In fact, the inequality is defined for convex function  $\varrho : [l_1, l_2] \rightarrow \mathbb{R}$  by

$$(1) \quad \varrho\left(\frac{l_1+l_2}{2}\right) \leq \int_{l_1}^{l_2} \frac{\varrho(\eta)}{l_2-l_1} d\eta \leq \frac{\varrho(l_1)+\varrho(l_2)}{2}.$$

In particular, studies on the right and left sides of the H-II contribute to the literature. For example, Dragomir *et al.* proved refinements and extensions for Midpoint type inequalities (MI) and Trapezoid type inequalities (TI) with the help of the bounds of the twice differentiable functions in [11] and [12], respectively. Fractional calculus is an successful apparatus to clarify physical wonders additionally real-world issues. Fractional derivative and integral operators not as it were varied from each other in terms of peculiarity, territory, and bits but moreover brought advancements to fractional analysis in terms of their utilization zones and spaces [22, 15, 1].

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Fractional integrals solved many integrals in mathematics. Fractional integral types, which are also used in the field of inequality, have provided new extensions, refinements, and, generalizations in this field [13, 3, 21, 16, 9, 18]. In some studies, by using the convexity of the function, in some research, by making use of the bounds of the second derivative, many studies that will contribute to the literature have been made. There are many generalizations of this type about the well-known H-HII with the help of fractional integrals in the literature. For instance, the authors in [17] consider H-HII (1) as the form

$$(2) \quad \varrho\left(\frac{\lambda_1 + \lambda_2}{2}\right) \leq \int_0^1 \varrho[(1 - \eta)\lambda_1 + \eta\lambda_2] d\eta \leq \frac{\varrho(\lambda_1) + \varrho(\lambda_2)}{2},$$

for convex function  $\varrho$ . In 2016, Chen obtained extensions of the H-HII for convex functions involving Riemann-Liouville fractional integrals [7]. Mihai *et al.* studied the H-HII (1) for the classes of convex, log-convex and log-concave functions [19]. Budak *et al.* gave bounds for the left and right hand sides of fractional Hermite-Hadamard [4]. In [8], the extensions of the Riemann-Liouville fractional H-HII are given for harmonic convex functions. Some TII and MII are presented for generalized fractional integrals [5]. Also You *et al.* [24] considered some new H-HII for harmonic convex functions via generalized fractional integrals. Mumcu *et al.* proved H-HII via generalized proportional fractional integrals [20]. In [2], the authors obtained new refinements of H-HII for strongly convex functions.

In this article, we will give refinements, extensions, and generalizations of H-HII (1) with the aid of the functions that have the conditions

$$(3) \quad \varrho'(\lambda_1 + \lambda_2 - \tau) - \varrho'(\tau) \geq 0, \quad \tau \in \left[\lambda_1, \frac{\lambda_1 + \lambda_2}{2}\right],$$

involving  $\psi$ -Hilfer fractional integrals. We will provide the necessary preliminary information about mentioned H-HII via  $\psi$ -Hilfer fractional integrals.

In Section 2, we present preliminary information and results such as definition of Riemann-Liouville fractional integrals, H-HII based on Riemann-Liouville fractional integrals, bounds of TII and MII for Riemann and Riemann-Liouville integrals,  $\psi$ -Hilfer integral definitions and H-HII involving  $\psi$ -Hilfer integral definitions. In the main results section 3, with help of bounds of second derivative functions, we will obtain improvements and generalizations of TII and MII using fractional integrals of a function with respect to another function, which is the main purpose of our article. In addition, it has been shown which inequalities are generalized among these inequalities obtained with the help of special choices in Section 3. We will

also observe the generalized  $\psi$ -Hilfer fractional H-HI under different conditions with application. Finally, we will give some suggestions to the reader in the conclusion section 4.

## 2. PRELIMINARIES

First, mathematical preliminaries of fractional calculus theory and bounded functions will be presented as follows. Let  $\varrho \in L_1[\imath_1, \imath_2]$ . The Riemann-Liouville integrals  $\mathbb{J}_{\imath_1+}^{\ell}\varrho$  and  $\mathbb{J}_{\imath_2-}^{\ell}\varrho$  of order  $\ell > 0$  with  $\imath_1 \geq 0$  are introduced by

$$\begin{aligned}\mathbb{J}_{\imath_1+}^{\ell}\varrho(\mathfrak{r}) &= \int_{\imath_1}^{\mathfrak{r}} \frac{(\mathfrak{r}-\eta)^{\ell-1}}{\Gamma(\ell)} \varrho(\eta) \, d\eta, & \mathfrak{r} > \imath_1, \\ \mathbb{J}_{\imath_2-}^{\ell}\varrho(\mathfrak{r}) &= \int_{\mathfrak{r}}^{\imath_2} \frac{(\eta-\mathfrak{r})^{\ell-1}}{\Gamma(\ell)} \varrho(\eta) \, d\eta, & \mathfrak{r} < \imath_2,\end{aligned}$$

respectively. Here  $\mathbb{J}_{\imath_1+}^0\varrho(\mathfrak{r}) = \mathbb{J}_{\imath_2-}^0\varrho(\mathfrak{r}) = \varrho(\mathfrak{r})$  [22, 15]. Sarikaya *et al.* first give the following interesting integral inequalities of Hermite-Hadamard type involving Riemann-Liouville fractional integrals in [23].

**Theorem 2.1** ([23]). *Let  $\varrho : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be a positive mapping with  $0 \leq \imath_1 < \imath_2$  and  $\varrho \in L_1[\imath_1, \imath_2]$ . If  $\varrho$  is a convex function on  $[\imath_1, \imath_2]$ , then the following inequalities involving Riemann-Liouville fractional integrals hold:*

$$(4) \quad \varrho\left(\frac{\imath_1 + \imath_2}{2}\right) \leq \frac{\Gamma(\ell+1)}{2(\imath_2 - \imath_1)^{\ell}} \left[ \mathbb{J}_{\imath_1+}^{\ell}\varrho(\imath_2) + \mathbb{J}_{\imath_2-}^{\ell}\varrho(\imath_1) \right] \leq \frac{\varrho(\imath_1) + \varrho(\imath_2)}{2}, \quad \ell > 0.$$

The inequalities of the MII in [11] and the boundaries of TII in [12] are obtained in Theorems 2.2 and 2.3.

**Theorem 2.2** ([11]). *Let  $\varrho : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be a twice differentiable mapping such that there exists real constants  $m_{\circ}$  and  $m^{\circ}$  so that  $m_{\circ} \leq \varrho'' \leq m^{\circ}$ . Then, the following inequalities hold*

$$(5) \quad m_{\circ} \frac{(\imath_2 - \imath_1)^2}{24} \leq \frac{\varrho(\imath_1) + \varrho(\imath_2)}{2} - \int_{\imath_1}^{\imath_2} \frac{\varrho(\eta)}{\imath_2 - \imath_1} \, d\eta \leq m^{\circ} \frac{(\imath_2 - \imath_1)^2}{24}.$$

**Theorem 2.3** ([10]). *Let the conditions of Theorem 2.2 be satisfied. Then the following inequalities yield,*

$$(6) \quad m_{\circ} \frac{(\imath_2 - \imath_1)^2}{24} \leq \int_{\imath_1}^{\imath_2} \frac{\varrho(\eta)}{\imath_2 - \imath_1} \, d\eta - \varrho\left(\frac{\imath_1 + \imath_2}{2}\right) \leq m^{\circ} \frac{(\imath_2 - \imath_1)^2}{24}.$$

Chen presented extension and refinement of the TII and MII for convex mappings utilizing Riemann-Liouville fractional integrals [7].

**Theorem 2.4** ([7]). *Let  $\varrho : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be a positive, twice differentiable mapping with  $\imath_1 < \imath_2$  and  $\varrho \in L_1[\imath_1, \imath_2]$  if  $\varrho''$  is bounded  $[\imath_1, \imath_2]$  then we get*

$$\begin{aligned}
 (7) \quad & \frac{m_\circ \ell}{2(\imath_2 - \imath_1)^\ell} \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \left( \frac{\imath_1 + \imath_2}{2} - \eta \right)^2 \left[ (\imath_2 - \eta)^{\ell-1} + (\imath_1 - \eta)^{\ell-1} \right] d\eta \\
 & \leq \frac{\Gamma(\ell+1)}{2(\imath_2 - \imath_1)^\ell} \left[ \mathbb{J}_{\imath_1+}^\varphi \varrho(\imath_2) + \mathbb{J}_{\imath_1-}^\varphi \varrho(\imath_1) \right] - \varrho \left( \frac{\imath_1 + \imath_2}{2} \right) \\
 & \leq \frac{m^\circ \ell}{2(\imath_2 - \imath_1)^\ell} \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \left( \frac{\imath_1 + \imath_2}{2} - \eta \right)^2 \left[ (\imath_2 - \eta)^{\ell-1} + (\imath_1 - \eta)^{\ell-1} \right] d\eta,
 \end{aligned}$$

for  $\ell > 0$ , where

$$(8) \quad m_\circ = \inf_{\mathfrak{r} \in [\imath_1, \imath_2]} \varrho''(\mathfrak{r}), \quad m^\circ = \sup_{\mathfrak{r} \in [\imath_1, \imath_2]} \varrho''(\mathfrak{r}).$$

**Theorem 2.5** ([7]). *Assume the conditions of Theorem 2.3. Then the following inequality is obtained.*

$$\begin{aligned}
 (9) \quad & \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \frac{-m^\circ \ell (\eta - \imath_1)(\imath_2 - \eta)}{2(\imath_2 - \imath_1)^\ell} \left[ (\imath_2 - \eta)^{\ell-1} + (\imath_1 - \eta)^{\ell-1} \right] d\eta \\
 & \leq \frac{\Gamma(\ell+1)}{2(\imath_2 - \imath_1)^\ell} \left[ \mathbb{J}_{\imath_1+}^\varphi \varrho(\imath_2) + \mathbb{J}_{\imath_2-}^\varphi \varrho(\imath_1) \right] - \frac{\varrho(\imath_1) + \varrho(\imath_2)}{2} \\
 & \leq \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \frac{-m_\circ \ell (\eta - \imath_1)(\imath_2 - \eta)}{2(\imath_2 - \imath_1)^\ell} \left[ (\imath_2 - \eta)^{\ell-1} + (\imath_1 - \eta)^{\ell-1} \right] d\eta,
 \end{aligned}$$

for  $\ell > 0$ , where  $m_\circ$  and  $m^\circ$  are defined in Equation (8).

The Definitions of the following  $\psi$ -Hilfer fractional integrals are given in [22, 15].

**Definition 2.6** ([15, 22]). Let  $\psi : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be an increasing and positive monotone function on  $(\imath_1, \imath_2]$ , having a continuous derivative  $\psi'(\mathfrak{r})$  on  $(\imath_1, \imath_2)$ . The left-sided and right-sided fractional integrals of  $\varrho$  with respect to the function  $\psi$  on  $[\imath_1, \imath_2]$  of order  $\ell > 0$  are defined by

$$\begin{aligned}
 \mathbb{I}_{\imath_1+; \psi}^\ell \varrho(\mathfrak{r}) &= \int_{\imath_1}^{\mathfrak{r}} \frac{\psi'(\eta)}{\Gamma(\ell)(\psi(\mathfrak{r}) - \psi(\eta))^{1-\ell}} \varrho(\eta) d\eta, & \mathfrak{r} > \imath_1, \\
 \mathbb{I}_{\imath_2-; \psi}^\ell \varrho(\mathfrak{r}) &= \int_{\mathfrak{r}}^{\imath_2} \frac{\psi'(\eta)}{\Gamma(\ell)(\psi(\eta) - \psi(\mathfrak{r}))^{1-\ell}} \varrho(\eta) d\eta, & \mathfrak{r} < \imath_2
 \end{aligned}$$

respectively, provided that the integral exists.

Jlelli *et al.* gave the following H-II for  $\psi$ -Hilfer fractional integrals in [14].

**Theorem 2.7.** *Let  $\psi$  is defined in Definition 2.7 with the same features with having a continuous derivative  $\psi'(\mathbf{r})$  on  $(\imath_1, \imath_2)$ . Let  $\varrho$  is a convex function on  $[\imath_1, \imath_2]$  and  $\ell > 0$ , then the following inequalities hold*

$$(10) \quad \varrho\left(\frac{\imath_1 + \imath_2}{2}\right) \leq \frac{\Gamma(\ell+1)}{4[\psi(\imath_2) - \psi(\imath_1)]^\ell} \left[ \mathbb{I}_{\imath_1+; \psi}^\ell \widehat{\varrho}(\imath_2) + \mathbb{I}_{\imath_2-; \psi}^\ell \widehat{\varrho}(\imath_1) \right] \leq \frac{\varrho(\imath_1) + \varrho(\imath_2)}{2},$$

where

$$(11) \quad \widehat{\varrho}(\mathbf{r}) = \varrho(\mathbf{r}) + \varrho(\imath_1 + 2 - \mathbf{r}).$$

Budak gave the following new version of H-HI with the aid of the  $\psi$ -Hilfer fractional integrals [6].

**Theorem 2.8** ([6]). *Let the assumptions of Theorem 2.7 hold. Then we have*

$$(12) \quad \varrho\left(\frac{\imath_1 + \imath_2}{2}\right) \leq \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell} \left[ \mathbb{I}_{\left(\frac{\imath_1 + \imath_2}{2}\right)+; \psi}^\ell \widehat{\varrho}(\imath_2) + \mathbb{I}_{\left(\frac{\imath_1 + \imath_2}{2}\right)-; \psi}^\ell \widehat{\varrho}(\imath_1) \right] \leq \frac{\varrho(\imath_1) + \varrho(\imath_2)}{2},$$

where  $\widehat{\varrho}$  is defined with Equation (11) and

$$(13) \quad \mathcal{F}_\psi^\ell = \left[ \psi(\imath_2) - \psi\left(\frac{\imath_1 + \imath_2}{2}\right) \right]^\ell + \left[ \psi\left(\frac{\imath_1 + \imath_2}{2}\right) - \psi(\imath_1) \right]^\ell.$$

### 3. MAIN RESULTS

Let's assume the properties of the  $\psi$  function that we will use in this section as follows. Let  $\psi : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be an increasing and positive monotone function on  $(\imath_1, \imath_2)$  and a continuous derivative  $\psi'(\mathbf{r})$  on  $(\imath_1, \imath_2)$ .

**Theorem 3.1.** *Let  $\varrho : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be a twice differentiable mapping such that there exists real constants  $m_\circ$  and  $m^\circ$  so that  $m_\circ \leq \varrho'' \leq m^\circ$ . Then, the following inequalities hold*

$$(14) \quad \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \frac{m_\circ \ell \mathcal{F}_\psi(\eta)}{2\mathcal{F}_\psi^\ell} \left(\frac{\imath_1 + \imath_2}{2} - \eta\right)^2 d\eta$$

$$\leq \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell} \left[ \mathbb{I}_{\left(\frac{\imath_1 + \imath_2}{2}\right)+; \psi}^\ell \widehat{\varrho}(\imath_2) + \mathbb{I}_{\left(\frac{\imath_1 + \imath_2}{2}\right)-; \psi}^\ell \widehat{\varrho}(\imath_1) \right] - \varrho\left(\frac{\imath_1 + \imath_2}{2}\right)$$

$$\leq \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \frac{m^\circ \ell \mathcal{F}_\psi(\eta)}{2\mathcal{F}_\psi^\ell} \left(\frac{\imath_1 + \imath_2}{2} - \eta\right)^2 d\eta,$$

where  $\mathcal{F}_\psi^\ell$  is defined by Equation (13) and

$$(15) \quad \mathcal{F}_\psi^\ell(\mathbf{r}) = (\psi(\imath_2) - \psi(\imath_1 + \imath_2 - \mathbf{r}))^{\ell-1} \psi'(\imath_1 + \imath_2 - \mathbf{r}) + (\psi(\mathbf{r}) - \psi(\imath_1))^{\ell-1} \psi'(\mathbf{r}).$$

*Proof.* With the aid of the Definition 2.6, we get

$$\begin{aligned}
 & \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell(1)} \left[ \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)^+; \psi}^\ell \widehat{\varrho}(i_2) + \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)^-; \psi}^\ell \widehat{\varrho}(i_1) \right] \\
 &= \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell(1)} \left[ \frac{1}{\Gamma(\ell)} \int_{\frac{i_1+i_2}{2}}^{i_2} (\psi(i_2) - \psi(\eta))^{\ell-1} \psi'(\eta) \widehat{\varrho}(\eta) \, d\eta \right. \\
 & \quad \left. + \frac{1}{\Gamma(\ell)} \int_{i_1}^{\frac{i_1+i_2}{2}} (\psi(\eta) - \psi(i_1))^{\ell-1} \psi'(\eta) \widehat{\varrho}(\eta) \, d\eta \right] \\
 (16) \quad &= \frac{\ell}{2\mathcal{F}_\psi^\ell(1)} \left[ \int_{i_1}^{\frac{i_1+i_2}{2}} (\psi(i_2) - \psi(i_1 + i_2 - \eta))^{\ell-1} \psi'(i_1 + i_2 - \eta) \widehat{\varrho}(i_1 + i_2 - \eta) \, d\eta \right. \\
 & \quad \left. + \int_{i_1}^{\frac{i_1+i_2}{2}} (\psi(\eta) - \psi(i_1))^{\ell-1} \psi'(\eta) \widehat{\varrho}(\eta) \, d\eta \right] \\
 &= \frac{\ell}{2\mathcal{F}_\psi^\ell} \int_{i_1}^{\frac{i_1+i_2}{2}} \left[ (\psi(i_2) - \psi(i_1 + i_2 - \eta))^{\ell-1} \psi'(i_1 + i_2 - \eta) \right. \\
 & \quad \left. + (\psi(\eta) - \psi(i_1))^{\ell-1} \psi'(\eta) \right] (\varrho(\eta) + \varrho(i_1 + i_2 - \eta)) \, d\eta \\
 &= \frac{\ell}{2\mathcal{F}_\psi^\ell} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_\psi(\eta) [\varrho(\eta) + \varrho(i_1 + i_2 - \eta)] \, d\eta.
 \end{aligned}$$

We have

$$\begin{aligned}
 (17) \quad & \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell} \left[ \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)^+; \psi}^\ell \widehat{\varrho}(i_2) + \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)^-; \psi}^\ell \widehat{\varrho}(i_1) \right] - \varrho\left(\frac{i_1+i_2}{2}\right) \\
 &= \frac{\ell}{2\mathcal{F}_\psi^\ell} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_\psi(\eta) \left[ \varrho(\eta) + \varrho(i_1 + i_2 - \eta) - 2\varrho\left(\frac{i_1+i_2}{2}\right) \right] \, d\eta.
 \end{aligned}$$

By using the facts that

$$\begin{aligned}
 \varrho(\mathfrak{r}) - \varrho\left(\frac{i_1+i_2}{2}\right) &= \int_{\frac{i_1+i_2}{2}}^{\mathfrak{r}} \varrho'(\eta) \, d\eta, \\
 \varrho(i_1 + i_2 - t) - \varrho\left(\frac{i_1+i_2}{2}\right) &= \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-t} \varrho'(\eta) \, d\eta,
 \end{aligned}$$

we have

$$\begin{aligned}
 (18) \quad & \varrho(t) + \varrho(i_1 + i_2 - \mathfrak{r}) - 2\varrho\left(\frac{i_1+i_2}{2}\right) \\
 &= \int_{\frac{i_1+i_2}{2}}^t \varrho'(\eta) \, d\eta + \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\mathfrak{r}} \varrho'(\eta) \, d\eta
 \end{aligned}$$

$$\begin{aligned} &= \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\tau} \varrho'(\eta) \, d\eta - \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\tau} \varrho'(i_1+i_2-\eta) \, d\eta \\ &= \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\tau} [\varrho'(s) - \varrho'(i_1+i_2-\eta)] \, d\eta. \end{aligned}$$

We also get

$$(19) \quad \varrho'(\tau) - \varrho'(i_1+i_2-\tau) = \int_{i_1+i_2-\tau}^{\tau} \varrho''(\eta) \, d\eta.$$

By utilizing  $m_\circ \leq \varrho''(\tau) \leq m^\circ$  ( $\forall \tau \in [i_1, i_2]$ ), with the aid of the equality (19), we obtain

$$\int_{i_1+i_2-\tau}^{\tau} m_\circ \, d\eta \leq \int_{i_1+i_2-\tau}^{\tau} \varrho''(\eta) \, d\eta \leq \int_{i_1+i_2-\tau}^{\tau} m^\circ \, d\eta,$$

which gives

$$m_\circ(2\tau - i_1 - i_2) \leq \varrho'(\tau) - \varrho'(i_1+i_2-\tau) \leq m^\circ(2\tau - i_1 - i_2).$$

From equality (18), we define

$$\begin{aligned} m_\circ \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\tau} (2\eta - i_1 - i_2) \, d\eta &\leq \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\tau} [\varrho'(\eta) - \varrho'(i_1+i_2-\eta)] \, d\eta \\ &\leq m^\circ \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\tau} (2\eta - i_1 - i_2) \, d\eta. \end{aligned}$$

That is,

$$(20) \quad m_\circ \left( \frac{i_1+i_2}{2} - \tau \right)^2 \leq \varrho(\tau) + \varrho(i_1+i_2-\tau) - 2\varrho\left(\frac{i_1+i_2}{2}\right) \leq m^\circ \left( \frac{i_1+i_2}{2} - \tau \right)^2.$$

Multiplying the inequality (20) by  $\frac{\ell \mathcal{F}_\psi(\tau)}{2\mathcal{F}_\psi^\ell}$  and then integrating with respect to  $\tau$  on the interval  $\left[ i_1, \frac{i_1+i_2}{2} \right]$ , we possess

$$\begin{aligned} &\frac{m_\circ \ell}{2\mathcal{F}_\psi^\ell} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_\psi(\eta) \left( \frac{i_1+i_2}{2} - \eta \right)^2 \, d\eta \\ &\leq \frac{\ell}{2\mathcal{F}_\psi^\ell} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_\psi(\eta) \left[ \varrho(\eta) + \varrho(i_1+i_2-\eta) - 2\varrho\left(\frac{i_1+i_2}{2}\right) \right] \, d\eta \\ &\leq \frac{m^\circ \ell}{2\mathcal{F}_\psi^\ell} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_\psi(\eta) \left( \frac{i_1+i_2}{2} - \eta \right)^2 \, d\eta. \end{aligned}$$

With help of the equation (17), we obtain the desired result. □

**Example 3.2.** Define function  $\varrho : [0.1, 1] \rightarrow \mathbb{R}$  by  $\varrho(\tau) = \frac{1}{\tau}$  with  $[\imath_1, \imath_2] = [0.1, 1]$ . Without a doubt  $\varrho$  is a twice differentiable map and

$$m_\circ = 1 \leq \varrho''(\tau) = \frac{2}{\tau^3} \leq 10 = m^\circ.$$

Now, by using (13), (15) and consider  $\psi(\tau) = \tau$ , we have

$$\begin{aligned} \mathcal{F}_\psi^\ell &= \left[ \psi(\imath_2) - \psi\left(\frac{\imath_1 + \imath_2}{2}\right) \right]^\ell + \left[ \psi\left(\frac{\imath_1 + \imath_2}{2}\right) - \psi(\imath_1) \right]^\ell \\ &= \left[ \psi(1) - \psi\left(\frac{1.1}{2}\right) \right]^\ell + \left[ \psi\left(\frac{1.1}{2}\right) - \psi(0.1) \right]^\ell \simeq \begin{cases} 1.7742, & \ell = 0.15, \\ 1.3416, & \ell = 0.50, \\ 0.9366, & \ell = 0.95, \end{cases} \end{aligned}$$

$$\begin{aligned} \mathcal{F}_\psi(\tau) &= (\psi(\imath_2) - \psi(\imath_1 + \imath_2 - \tau))^{\ell-1} \psi'(\imath_1 + \imath_2 - \tau) + (\psi(\tau) - \psi(\imath_1))^{\ell-1} \psi'(\tau) \\ &= \left[ (1 - \psi(1.1 - \tau))^{\ell-1} \right] + (\psi(\tau) - \psi(0.1))^{\ell-1} \simeq \begin{cases} 4.3579, & \ell = 0.15, \\ 3.1622, & \ell = 0.50, \\ 2.0937, & \ell = 0.95, \end{cases} \end{aligned}$$

for  $\tau = 0.5$ , and

**Table 1.** Numerical results of Inequalities (14) for  $\ell \in \{0.15, 0.5, 0.95\}$ .

$\tau$	Left side	Ineqs. (14)	Right side	Left side	Ineqs. (14)	Right side	Left side	Ineqs. (14)	Right side
	$\ell = 0.15$			$\ell = 0.5$			$\ell = 0.95$		
	0.1000	0.2910	2.9095	1.5924	0.2770	2.7700	0.9757	0.2676	2.6760
0.2000	0.2910	2.9095	1.5924	0.2770	2.7700	0.9757	0.2676	2.6760	0.6427
0.3000	0.2910	2.9095	1.5924	0.2770	2.7700	0.9757	0.2676	2.6760	0.6427
0.4000	0.2910	2.9095	1.5924	0.2770	2.7700	0.9757	0.2676	2.6760	0.6427
0.5000	0.2910	2.9095	1.5924	0.2770	2.7700	0.9757	0.2676	2.6760	0.6427

$$\begin{aligned} \frac{m_\circ \ell}{2\mathcal{F}_\psi^\ell} \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \mathcal{F}_\psi(\eta) \left( \frac{\imath_1 + \imath_2}{2} - \eta \right)^2 d\eta &\simeq \begin{cases} 0.2909, & \ell = 0.15, \\ 0.2770, & \ell = 0.50, \\ 0.2676, & \ell = 0.95, \end{cases} \\ &\leq \begin{cases} 1.5923, & \ell = 0.15, \\ 0.9756, & \ell = 0.50, \\ 0.6426, & \ell = 0.95, \end{cases} \\ &\simeq \frac{\ell}{2\mathcal{F}_\psi^\ell} \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \mathcal{F}_\psi(\eta) \left[ \varrho(\eta) + \varrho(\imath_1 + \imath_2 - \eta) - 2\varrho\left(\frac{\imath_1 + \imath_2}{2}\right) \right] d\eta \\ &\leq \begin{cases} 2.9095, & \ell = 0.15, \\ 2.7700, & \ell = 0.50, \\ 2.6760, & \ell = 0.95, \end{cases} \simeq \frac{m^\circ \ell}{2\mathcal{F}_\psi^\ell} \int_{\imath_1}^{\frac{\imath_1 + \imath_2}{2}} \mathcal{F}_\psi(\eta) \left( \frac{\imath_1 + \imath_2}{2} - \eta \right)^2 d\eta. \end{aligned}$$

Table 1 shows these results. Figures 1 and 2a, 2b, 2c show graphical representation of the variables. Thus, Inequalities (14) in Theorem 3.1 hold.



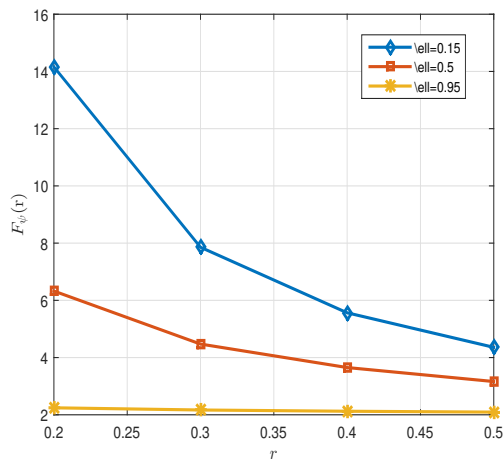


Figure 1. 2D-graph of  $\mathcal{F}_\psi$  for  $r \in [0.1, 1]$  in Example 3.2.

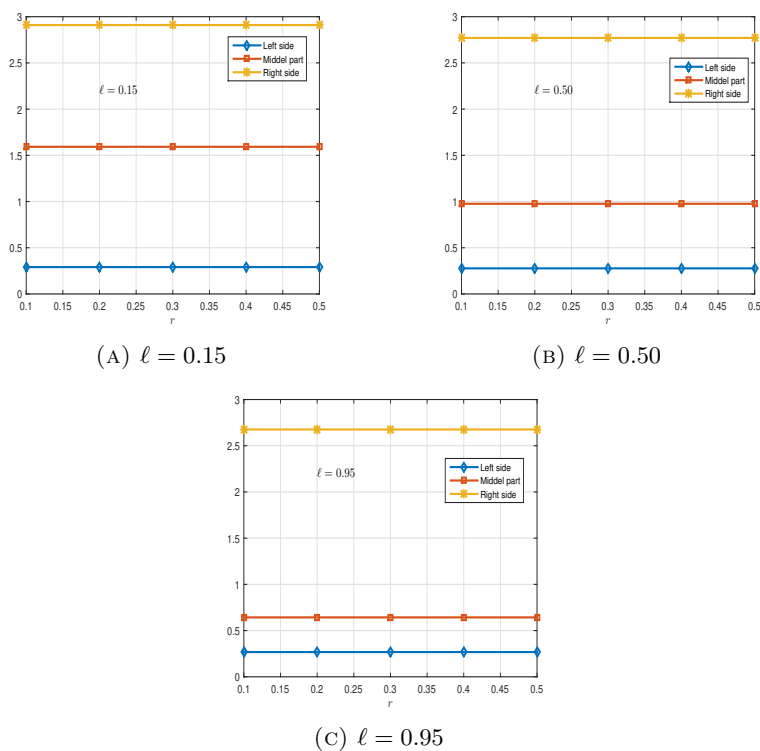


Figure 2. Graphical representation of inequalities (14) for  $\ell \in \{0.15, 0.50, 0.95\}$ .

**Corollary 3.3.** *If we choose  $\psi(\tau) = \tau$  in Theorem 3.1, then inequalities (14) is reduced to inequality (7).*

**Theorem 3.4.** *Let  $\varrho : [\imath_1, \imath_2] \rightarrow \mathbb{R}$  be a twice differentiable mapping such that there exists real constants  $m_\circ$  and  $m^\circ$  so that  $m_\circ \leq \varrho'' \leq m^\circ$ . Then, we establish*

$$\begin{aligned}
 (21) \quad & \frac{m_\circ \ell}{2\mathcal{F}_\psi^\ell} \int_{\imath_1}^{\frac{\imath_1+\imath_2}{2}} \mathcal{F}_\psi(\eta)(\imath_2 - \eta)(\eta - \imath_1) d\eta \\
 & \leq \frac{\varrho(\imath_1)+\varrho(\imath_2)}{2} - \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell} \left[ \mathbb{I}_{\left(\frac{\imath_1+\imath_2}{2}\right)^+; \psi}^\ell \widehat{\varrho}(\imath_2) + \mathbb{I}_{\left(\frac{\imath_1+\imath_2}{2}\right)^-; \psi}^\ell \widehat{\varrho}(\imath_1) \right] \\
 & \leq \frac{m^\circ \ell}{2\mathcal{F}_\psi^\ell} \int_{\imath_1}^{\frac{\imath_1+\imath_2}{2}} \mathcal{F}_\psi(\eta)(\imath_2 - \eta)(\eta - \imath_1) d\eta
 \end{aligned}$$

where  $\mathcal{F}_\psi$  is stated by as in (15).

*Proof.* By the equation (16), we have

$$\begin{aligned}
 (22) \quad & \frac{\varrho(\imath_1)+\varrho(\imath_2)}{2} - \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell} \left[ \mathbb{I}_{\left(\frac{\imath_1+\imath_2}{2}\right)^+; \psi}^\ell \widehat{\varrho}(\imath_2) + \mathbb{I}_{\left(\frac{\imath_1+\imath_2}{2}\right)^-; \psi}^\ell \widehat{\varrho}(\imath_1) \right] \\
 & = \frac{\varrho(\imath_1)+\varrho(\imath_2)}{2} - \int_{\imath_1}^{\frac{\imath_1+\imath_2}{2}} \frac{\ell \mathcal{F}_\psi(\eta)}{2\mathcal{F}_\psi^\ell} [\varrho(\eta) + \varrho(\imath_1 + \imath_2 - \eta)] d\eta \\
 & = \int_{\imath_1}^{\frac{\imath_1+\imath_2}{2}} \frac{\ell \mathcal{F}_\psi(\eta)}{2\mathcal{F}_\psi^\ell} [\varrho(\imath_1) + \varrho(\imath_2) - (\varrho(\eta) + \varrho(\imath_1 + \imath_2 - \eta))] d\eta.
 \end{aligned}$$

With help of the equalities

$$\varrho(\imath_1) - \varrho(\tau) = - \int_{\imath_1}^{\tau} \varrho'(\eta) d\eta, \quad \varrho(\imath_2) - \varrho(\imath_1 + \imath_2 - \tau) = \int_{\imath_1 + \imath_2 - \tau}^{\imath_2} \varrho'(\eta) d\eta,$$

we have

$$\begin{aligned}
 (23) \quad & \varrho(\imath_1) + \varrho(\imath_2) - (\varrho(\tau) + \varrho(\imath_1 + \imath_2 - \tau)) = \int_{\imath_1 + \imath_2 - \tau}^{\imath_2} \varrho'(\eta) d\eta - \int_{\imath_1}^{\tau} \varrho'(\eta) d\eta \\
 & = \int_{\imath_1}^{\tau} \varrho'(\imath_1 + \imath_2 - \eta) d\eta - \int_{\imath_1}^{\tau} \varrho'(\eta) d\eta = \int_{\imath_1}^{\tau} [\varrho'(\imath_1 + \imath_2 - \eta) - \varrho'(\eta)] d\eta.
 \end{aligned}$$

We also obtain

$$(24) \quad \varrho'(\imath_1 + \imath_2 - \tau) - \varrho'(\tau) = \int_{\tau}^{\imath_1 + \imath_2 - \tau} \varrho''(\eta) d\eta.$$

By (24) and the condition that  $m_\circ \leq \varrho'' \leq m^\circ$ , we establish

$$(25) \quad m_\circ (\imath_1 + \imath_2 - 2\tau) \leq \varrho'(\tau) - \varrho'(\imath_1 + \imath_2 - \tau) \leq m^\circ (\imath_1 + \imath_2 - 2\tau).$$

From equality (23) and the inequality (25), we derive

$$\int_{i_1}^{\mathfrak{r}} m_{\circ}(i_1 + i_2 - 2\eta) \, d\eta \leq \int_{i_1}^{\mathfrak{r}} [\varrho'(\eta) - \varrho'(i_1 + i_2 - \eta)] \, d\eta \leq \int_{i_1}^{\mathfrak{r}} m^{\circ}(i_1 + i_2 - 2\eta) \, d\eta,$$

i.e.

$$m_{\circ}(i_2 - \mathfrak{r})(\mathfrak{r} - i_1) \leq \varrho(i_1) + \varrho(i_2) - (\varrho(\mathfrak{r}) + \varrho(i_1 + i_2 - \mathfrak{r})) \leq m^{\circ}(i_2 - \mathfrak{r})(\mathfrak{r} - i_1).$$

Multiplying the inequality (26) by  $\frac{\ell \mathcal{F}_{\psi}(\mathfrak{r})}{2\mathcal{F}_{\psi}^{\ell}}$  and then integrating with respect to  $\mathfrak{r}$  on the interval  $\left[ i_1, \frac{i_1+i_2}{2} \right]$ , we derive

$$\begin{aligned} (26) \quad \int_{i_1}^{\frac{i_1+i_2}{2}} \frac{m_{\circ}\ell(i_2-\eta)(\eta-i_1)}{2\mathcal{F}_{\psi}^{\ell}} \mathcal{F}_{\psi}(\eta) \, d\eta &\leq \frac{\varrho(i_1)+\varrho(i_2)}{2} - \frac{\Gamma(\ell+1)}{2\mathcal{F}_{\psi}^{\ell}} \left[ \mathbb{I}_{i_1+;\psi}^{\ell} \widehat{\varrho}(i_2) + \mathbb{I}_{i_2-;\psi}^{\ell} \widehat{\varrho}(i_1) \right] \\ &\leq \int_{i_1}^{\frac{i_1+i_2}{2}} \frac{m^{\circ}\ell(i_2-\eta)(\eta-i_1)}{2\mathcal{F}_{\psi}^{\ell}} \mathcal{F}_{\psi}(\eta) \, d\eta. \end{aligned}$$

This completes the proof. □

**Corollary 3.5.** *If we take  $\psi(\mathfrak{r}) = \mathfrak{r}$  in Theorem 3.4, then the inequality (21) reduce to the inequality (9).*

In the next theorem, we will examine the proof of Theorem 2.7 under different conditions.

**Theorem 3.6.** *Let  $\varrho : [i_1, i_2] \rightarrow \mathbb{R}$  be a positive and differentiable function and  $\varrho \in L_1 [i_1, i_2]$ . If condition (3) holds, then the following inequalities via fractional integrals hold*

$$(27) \quad \varrho\left(\frac{i_1+i_2}{2}\right) \leq \frac{\Gamma(\ell+1)}{2\mathcal{F}_{\psi}^{\ell}} \left[ \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)+;\psi}^{\ell} \widehat{\varrho}(i_2) + \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)-;\psi}^{\ell} \widehat{\varrho}(i_1) \right] \leq \frac{\varrho(i_1)+\varrho(i_2)}{2}.$$

*Proof.* Thank to of the equalities (17) and (18), we posses

$$\begin{aligned} &\frac{\Gamma(\ell+1)}{4[\psi(i_2)-\psi(i_1)]^{\ell}} \left[ \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)+;\psi}^{\ell} \widehat{\varrho}(i_2) + \mathbb{I}_{\left(\frac{i_1+i_2}{2}\right)-;\psi}^{\ell} \widehat{\varrho}(i_1) \right] - \varrho\left(\frac{i_1+i_2}{2}\right) \\ &= \frac{\ell}{2\mathcal{F}_{\psi}^{\ell}} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_{\psi}(\eta) \left[ \varrho(\eta) + \varrho(i_1 + i_2 - \eta) - 2\varrho\left(\frac{i_1+i_2}{2}\right) \right] \, d\eta \\ &= \frac{\ell}{2\mathcal{F}_{\psi}^{\ell}} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_{\psi}(\eta) \left[ \int_{\frac{i_1+i_2}{2}}^{i_1+i_2-\eta} [\varrho'(\nu) - \varrho'(i_1 + i_2 - \nu)] \, d\nu \right] \, d\eta \\ &= \frac{\ell}{2\mathcal{F}_{\psi}^{\ell}} \int_{i_1}^{\frac{i_1+i_2}{2}} \mathcal{F}_{\psi}(\eta) \left[ \int_{\eta}^{\frac{i_1+i_2}{2}} [\varrho'(i_1 + i_2 - \nu) - \varrho'(\nu)] \, d\nu \right] \, d\eta \geq 0, \end{aligned}$$

which proves the first inequality in (27). Similarly, by the equalities (22) and (23), we establish

$$\begin{aligned} & \frac{\varrho(\imath_1) + \varrho(\imath_2)}{2} - \frac{\Gamma(\ell+1)}{2\mathcal{F}_\psi^\ell} \left[ \mathbb{I}_{\left(\frac{\imath_1+\imath_2}{2}\right)_+; \psi}^\ell \widehat{\varrho}(\imath_2) + \mathbb{I}_{\left(\frac{\imath_1+\imath_2}{2}\right)_-; \psi}^\ell \widehat{\varrho}(\imath_1) \right] \\ &= \int_{\imath_1}^{\frac{\imath_1+\imath_2}{2}} \frac{\ell \mathcal{F}_\psi(\eta)}{2\mathcal{F}_\psi^\ell} [\varrho(\imath_1) + \varrho(\imath_2) - (\varrho(\eta) + \varrho(\imath_1 + \imath_2 - \eta))] d\eta \\ &= \int_{\imath_1}^{\frac{\imath_1+\imath_2}{2}} \frac{\ell \mathcal{F}_\psi(\eta)}{2\mathcal{F}_\psi^\ell} \left[ \int_{\imath_1}^\eta [\varrho'(\imath_1 + \imath_2 - \nu) - \varrho'(\nu)] d\nu \right] d\eta \geq 0 \end{aligned}$$

The proof of the Theorem 3.6 completed.  $\square$

#### 4. CONCLUSION

In the present paper, we presented new H-HI based on  $\psi$ -Hilfer fractional integral operators with the aid of the mappings whose twice differentiable are bounded. Moreover, the  $\psi$ -Hilfer fractional H-HI was obtained under different conditions. As can be seen from our article, curious readers can use the conditional  $m_\circ \leq \varrho''(\mathfrak{r}) \leq m^\circ$  for all  $\mathfrak{r} \in [\imath_1, \imath_2]$  instead of convexity, and they can try to find better bounds using the condition (3). What's more, mathematicians will be able to study different types of fractional mappings. In addition, researchers will be able to derive new inequalities using different types of convexities.

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